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CONTROLLING SEDIMENT AND NUTRIENT LOSSES FROM PACIFIC NORTHWEST IRRIGATED AREAS

by

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16. ABSTRACT

General cropping pattern information has been assembled for major irrigated physiographic regions of Washington, Oregon, and Idaho, including irrigation system data and soil survey and land class information. Data have been assembled on physical factors leading to sediment and nutrient (phosphorus and nitrogen) losses from irrigated croplands, on methods of characterizing water application to and losses from such croplands, and on the economic techniques and/or factors for assessing the costs of selected pollution abatement practices. The report documents and compares many sources of information related to the estimation of sediment and nutrient losses. A method is proposed for measuring sediment (with associated phosphorus) and nitrogen losses from Pacific Northwest irrigated croplands. The technique attempts to incorporate dominant factors affecting erosional losses from typical Pacific Northwest lands, and also the spatial nonuniformity of nitrate leaching from furrow- and sprinkler-irrigated lands of the region. Nutrient loss estimates are generated for model farms in the Magic Valley (Idaho) and Umatilla (Oregon) areas, along with an economic analysis of selected pollution abatement practices. These results are compared to those from prior studies in the Yakima Valley (Washington) area. A discussion of general economic concepts related to the pollution abatement problem is also provided.

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FOREWORD

Environmental protection efforts dealing with agricultural and nonpoint sources have received increased emphasis with the passage of the Clean Water Act of 1977 and the subsequent implementation of the Rural Clean Water Program. As part of this Laboratory's research on the occurrence, movement, transformation, fate, impact, and control of environmental contaminants, data and analytical methodologies are developed to assess the causes and possible solutions of adverse environmental effects of irrigated agriculture.

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Efforts to achieve water quality goals include the identification and application of best management practices (BMPs) to control agriculturally related water pollutants. This report addresses the physical factors contributing to sediment and nutrient (phosphorus and nitrogen) losses from irrigated croplands, methods of characterizing water application to and losses from such croplands, and the economic techniques and/or factors for assessing the costs of selected pollution abatement practices. The methodology and techniques described will be useful in reaching technically sound and economically feasible environmental management decisions. This report should especially benefit environmental managers as they attempt to identify and implement pollution control strategies relevant to western irrigated agriculture.

Clinton W. Hall

Clinton W. Hall
Director
Robert S. Kerr Environmental
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ABSTRACT

General cropping pattern information has been assembled for major irrigated physiographic regions of Washington, Oregon and Idaho, as well as irrigation system characterization data. Sources of soil survey and land class information are discussed. Such information is useful in projecting cropping pattern and irrigation-system trends, and in establishing model farm characteristics for comparing physical and economic effects of proposed management systems.

Background information has been assembled on physical factors leading to sediment and nutrient (phosphorus and nitrogen) losses from irrigated croplands, and on methods of characterizing water application rates and losses. Economic techniques and/or factors for assessing the costs of selected pollution abatement practices are also discussed.

A relatively simple technique is proposed for assessing losses of nitrogen and of sediment (with associated phosphorus) from Pacific Northwest irrigated croplands. The technique attempts to incorporate dominant factors affecting erosional losses, as well as the spatial nonuniformity of nitrate leaching from furrow- and sprinkler-irrigated lands of the region.

Nutrient loss estimates are generated for model farms in the Magic Valley area of Idaho and the Umatilla area of Oregon, along with an economic analysis of selected pollution abatement practices. These results are compared to those from prior studies in the Yakima Valley of Washington.

The nutrient-loss estimation technique, and the model-farm approach to economic analysis, should be of aid to Section 208 (PL 92-500) planning and implementation programs in irrigated portions of the Pacific Northwest.

This report was submitted in fulfillment of Grant No. R805037 by Washington State University under the sponsorship of the U.S. Environmental Protection Agency. The report covers the period from February 22, 1977 to December 31, 1978, with work being completed as of June 1, 1979.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

CONTENTS

Foreword iii
Abstract iv
List of Figures vi
List of Tables vii
Relevant English Units and Metric Equivalents xii
Acknowledgments xiii
Executive Summary xiv

1. Introduction 1
2. Conclusions 3
3. Recommendations 6
4. Physical Data for Selected Physiographic Regions 8
5. Economic Concepts and Policies Related to Control of Pollution from Irrigated Agriculture 26
6. Sediment and Nutrient Loss Estimates (Background) 48
7. Sediment and Nutrient Loss Estimates (Recommended Approach) 93
8. Case Studies for Selected Pacific Northwest Areas 101

References 153
Bibliography 160

Appendix

A. Additional Physical and Economic Characterization Data for the Magic Valley Area of Idaho and the Umatilla Area of Oregon 165

6-1/2"
9-1/8"
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

FIGURES

Number **Page**

1 Potential alternatives in the choice between environmental quality and basic needs 28

2 Market supply and demand functions for a trade good 32

3 Adjustment in output that could result from recognition of environmental costs 34

4 Comparison of predicted and measured sediment losses from some Pacific Northwest irrigated lands 73

5 Water distribution for three uniformity coefficient values and 50 percent adequacy of irrigation 81

6 Water distribution with an 80 percent uniformity coefficient and 75 percent adequacy of irrigation 82

7 On-farm costs of reducing sediment loss using alternative control practices on Magic Valley Farm 1 114

8 On-farm costs of reducing nitrogen loss using alternative control practices on Magic Valley Farm 1 116

9 On-farm costs of reducing nitrogen loss using alternative control practices on the Umatilla Area model farm 126

10 The Yakima River Basin 129

11 Marginal costs of abating nitrogen leaching for various soil types in the long run 138

12 Schematic diagram of the Pfeiffer model for the Yakima River Basin 139

6-1/2"
BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES

Number **Page**

1 Pacific Northwest Irrigated Acreage, by Crop and State 12

2 Washington Irrigated Acreage, by Crop and Physiographic Area 13

3 Oregon Irrigated Acreage, by Crop and Physiographic Area 14

4 Idaho Irrigated Acreage, by Crop and Physiographic Area 15

5 Distribution of Irrigation Systems among Pacific Northwest Irrigated Acreage, 1975 21

6 Typical Rooting Depths for Major Crops of the Pacific Northwest 49

7 Typical Water Holding Capacities for Major Soil Types of the Pacific Northwest 50

8 Estimated Depletable Soil Moisture Values for Major Crops and Soil Types in the Magic Valley Area of Idaho and the Umatilla Area of Oregon 52

9 Estimated Numbers of Irrigations per Season for Major Crops and Soil Types in the Magic Valley Area of Idaho and the Umatilla Area of Oregon 53

10 Some Alternative Irrigation Systems for the Magic Valley and Umatilla Areas 56

11 Estimated Irrigation Efficiencies for Major Crops and Alternative Irrigation Systems in the Magic Valley 59

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Number **Page**

12 Estimated Percent Runoff and Deep Percolation for Major Crops and Alternative Irrigation Systems in the Magic Valley 61

13 Seasonal Net Irrigation Requirements for Major Crops in the Magic Valley and Umatilla Areas 66

14 Typical Fertilizer-Guide Nitrogen Recommendations for Selected Crops Grown in Major Irrigated Areas of the Pacific Northwest 80

15 Percent Deep Percolation for Selected Uniformity Coefficients and Adequacy Levels 83

16 Percent Deep Percolation for Tenth-Field Subunits at Selected Uniformity Coefficients and Adequacy Levels 85

17 Deep Percolation, Nitrogen Fertilizer Application, and Nitrate Leaching for Tenth-Field Subunits 89

18 A Comparison of Nitrate Leaching Estimates Obtained from Use of Three Different Techniques 91

19 Nitrate Leaching Denitrification Multipliers for Selected Saturated Hydraulic Conductivity Values and Corresponding Soil Textures . . . 92

20 Multipliers to the Base-Level Sediment Loss Values to Adjust for Selected Crop Types . . 95

21 Multipliers to the Base-Level Sediment Loss Values to Adjust for Selected Runoff Volumes 95

22 Multipliers to the Base-Level Sediment Loss Values to Adjust for Selected Soil Textures 96

23 Multipliers to the Base-Level Sediment Loss Values to Adjust for Selected Field Slopes 97

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Number		Page
24	Soil Textures and Slopes of the Magic Valley Model Farms	102
25	Cropping Patterns Defined for Magic Valley Model Farm 1	102
26	Net Returns, Water and Pollutant Losses, and Input Use for the Irrigation System Changes and Sediment Retention Devices on Magic Valley Farm 1	104
27	Net Returns, Water and Pollutant Losses, and Input Use for Cropping Pattern Changes, and Combination Irrigation System and Cropping Pattern Changes, for Magic Valley Farm 1 . .	110
28	Net Returns, Water and Pollutant Losses, and Input Use for Alternative Soil and Slope Conditions with Current Management and Farming Conditions in the Magic Valley . . .	118
29	Cropping Patterns Defined for the Umatilla Area Model Farm	120
30	Control Practices Used on the Umatilla Area Model Farm	121
31	Net Returns, Water and Pollutant Losses, and Input Use for the Control Practices Used on the Umatilla Area Model Farm	122
32	Capital Investment and Annual Operating Costs of Six Irrigation Systems	131
33	Estimated Irrigation Efficiencies and Deep Percolation Losses by Crop and Irrigation System, Gossett Study	133
34	Benchmark Solution, Yakima Valley Model Farm	134
35	Comparisons between Alternative Irrigation Systems, Yakima Valley Model Farm	135
36	Policies Selected by Pfeiffer for Analysis . .	142
37	Income, Resource Use, and Resultant Water Quality for Pfeiffer's Solutions 1 and 2 . .	143

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Number		Page
38	Summary of Pfeiffer's Benchmark Solution and of Solutions Meeting Yakima River Nitrogen and Temperature Goals	144
39	Income, Resource Use, and Water Quality Determined with Improved Management, Pfeiffer's Solution 3	146
A-1	Estimated Seasonal Runoff and Deep Percolation for Major Crops and Alternative Irrigation Systems in the Magic Valley	165
A-2	Estimated Seasonal Deep Percolation for Major Crops and Irrigation Systems in the Umatilla Area	166
A-3	Estimated Seasonal Water Application Requirements for Major Crops and Alternative Irrigation Systems in the Magic Valley	167
A-4	Estimated Seasonal Water Application Requirements for Major Crops and Irrigation Systems in the Umatilla Area	168
A-5	Phosphorus Fertilizer Application Rates for Major Crops in the Magic Valley and Umatilla Areas	168
A-6	Nitrogen Application Rates and Estimated Nitrate Leaching Losses for Major Crops and Irrigation Systems in the Umatilla Area	169
A-7	Estimated Sediment Loss for Major Crop Types and Alternative Irrigation Systems in the Magic Valley	170
A-8	Nitrogen Application Rates and Estimated Nitrate Leaching Losses for Major Crops and Alternative Irrigation Systems in the Magic Valley	171
A-9	Estimated per Acre Crop Production Costs for the Study Areas	172
A-10	Additional Crop Production Costs for the Study Areas	173

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Number **Page**

A-11 Yields and Prices for Crops Produced in the Study Areas 174

A-12 Estimated Energy Requirements for Pumping Irrigation Water in the Study Areas 175

A-13 Estimated per Acre Irrigation Labor Requirements for the Study Areas 176

A-14 Capital Investment and Annual Costs for the Present Furrow Irrigation System, Improved Furrow Irrigation System, and the Cut-Back Furrow Irrigation System on the Magic Valley Model Farm 177

A-15 Capital Investment and Annual Costs for the Pump-Back Furrow Irrigation System on the Magic Valley Model Farm 179

A-16 Capital Investment and Annual Costs for the Gated-Pipe Furrow Irrigation System on the Magic Valley Model Farm 180

A-17 Capital Investment and Annual Costs for the Multi-Set Furrow Irrigation System on the Magic Valley Model Farm 181

A-18 Capital Investment and Annual Costs for the Side-Roll Sprinkler Irrigation System on the Magic Valley Model Farm 183

A-19 Annual Costs for Filter Strips on the Magic Valley Model Farm 184

A-20 Estimated Annual Crop Production Costs in the Magic Valley 185

A-21 Capital Investment and Annual Costs for the Present Center-Pivot Sprinkler and the Improved Center-Pivot Sprinkler Systems on the Umatilla Area Model Farm 186

A-22 Estimated Annual Crop Production Costs in the Umatilla Area 187

9-1/8"
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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

RELEVANT ENGLISH UNITS AND METRIC EQUIVALENTS

English unit	Metric equivalent	Metric unit	English equivalent
1 inch	2.54 cm	1 cm	0.394 inch
1 foot	0.305 meter	1 meter	3.28 feet
1 acre	0.405 hectare	1 hectare	2.471 acres
1 acre-inch	102.8 cubic meters	1 cubic meter	0.00973 acre-inch
1 bushel	35.24 liters	1 liter	0.0284 bushels
1 ton	0.9072 tonne	1 tonne	1.102 ton
1 cwt	0.454 quintals	1 quintal	2.205 cwt
1 lb	0.454 kg	1 kg	2.205 lb
1 ton/acre	2.24 tonne/ha	1 tonne/ha	0.446 ton/acre
1 lb/acre	1.12 kg/ha	1 kg/ha	0.892 lb/acre
1 cwt/acre	1.12 quintal/ha	1 quintal/ha	0.892 cwt/acre
1 gallon	3.785 liters	1 liter	0.2642 gallons

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

EXECUTIVE SUMMARY

In Section 4 of this report, cropping pattern information is presented for major irrigated physiographic areas of the Pacific Northwest, and cropping pattern and irrigated acreage trends for the period 1959-1974 are summarized. These data emphasize the predominance of relatively nonpolluting hay and grain crops in many irrigated areas of the region, and assist focus on more highly erosive and more heavily fertilized row-crop areas. Also included are state-wide summaries of irrigation system information, and narrative highlights of irrigation system data for individual physiographic areas. These demonstrate that furrow irrigation still predominates in the region, despite rapid conversion to center-pivot sprinkler systems. Because of the uneven nature and incomplete coverage of soil survey and land classification information for physiographic areas of the region, no specific data are presented in this category. Sources of such information and their use in nutrient-loss estimates are discussed, however.

Section 5 reviews economic concepts and policies related to the control of pollution from irrigated agriculture. Community property rights and private property rights are contrasted, and costs of pollution are illustrated via supply and demand functions for trade goods. The concepts of externalities and opportunity costs are introduced prior to a discussion of benefits and methods of pollution abatement, and of income distribution problems. The difficulties of marketplace solutions to traditional pollutant abatement problems are stressed, and the transaction costs associated with various types of liability distribution are emphasized. Selected abatement implementation policies are reviewed, including effluent standards effluent taxes, subsidies, output taxes, and input taxes and/or limits. The section closes with a discussion of various methods and philosophies related to determining the "correct amount" of pollution abatement.

In Section 6, background material is summarized which relates to sediment and nutrient loss estimates for irrigated lands. The determination of irrigation requirements is included as a part of the information necessary for nutrient loss predictions, with major emphasis on the concept of irrigation efficiency (E), and on the subdivision of (1-E) values into runoff, deep percolation, and evaporative losses. Rooting

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

depths and water holding capacities are provided for selected crops and soil types typical of Pacific Northwest irrigated areas. These are combined into values for depletable soil moisture and numbers of irrigations for crop-soil combinations representative of the Magic Valley area of Idaho and the Umatilla area of Oregon. Allocation of efficiency, runoff, and deep percolation values for current and proposed irrigation systems is outlined, including correction for variations in slope class and soil type. Net irrigation requirements and seasonal water application estimates are provided for the two study areas listed above.

The effects of various factors on sediment and total phosphorus losses are also reviewed, including slope, stream size or percent runoff, tillage, set length, soil texture, and crop type. A methodology for predicting sediment losses is outlined, based upon assignment of a sediment-loss estimate for prescribed base-level conditions, and then assignment of multipliers to account for changes in sediment loss associated with variations in factors of the type just described. Total phosphorus loss is assumed to remain a constant proportion of sediment loss. This assumption will require refinement as sediment and phosphorus loss data become more widely available for irrigated areas of the region, but it serves as a suitable first approximation at present. Background information on nitrogen loss estimates (largely from University of California studies) is reviewed, and related to prior measurements for irrigated tracts in the Pacific Northwest. A methodology for predicting nitrate leaching losses is outlined, based on the amount of deep percolation and nitrogen fertilization, with corrections for nonuniformity of water application (by dealing with the amounts of deep percolation and nitrogen fertilization that might reasonably be expected for tenth-field subunits of each irrigated field) and for denitrification (as related to surface-soil texture).

Section 7 summarizes the recommended procedures for sediment, phosphorus, and nitrogen loss estimates for Pacific Northwest irrigated croplands.

In Section 8, the recommended procedures for sediment, phosphorus, and nitrogen losses are applied to two Pacific Northwest irrigated areas (the Magic Valley area of southcentral Idaho and the Umatilla area of northcentral Oregon). Model farms are established for each area. Various irrigation system and cropping pattern changes are evaluated with respect to the sediment and nutrient losses, and associated economic costs, which each would produce. For the Magic Valley, the use of filter strips, sediment ponds, and pump-back irrigation would all lie on the "efficiency frontier" curve representing sediment-loss abatement at minimum cost. Use of improved furrow management cut-back irrigation systems, and gated-pipe delivery

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

systems would also lie only slightly above the efficiency frontier curve, but conversion to side-roll sprinklers, multiset irrigation systems, or alternative cropping patterns would abate sediment loss only at considerably higher cost.

With respect to nitrogen loss abatement for the Magic Valley, use of improved furrow management, cut-back irrigation, or gated-pipe would all be on the efficiency frontier curve, and produce approximately 50 percent abatement (in the case of cut-back irrigation or use of gated-pipe systems) at relatively little cost. Further abatement of losses would require markedly higher costs per unit of abatement, however. For the Umatilla area, over 50 percent abatement of nitrogen losses could be affected through improved management of center-pivot systems at relatively little cost, but conversion to alternative cropping patterns would abate nitrogen losses only at considerable cost.

The remainder of this section summarizes the similar studies for the Yakima Valley of Washington. Gossett (1975) adopted a model-farm approach, with findings similar to those reported in this study for the Magic Valley area. He also evaluated the economic consequences of various abatement-implementation practices, including constraints or taxes on total nitrogen and sediment outflows from the farm, grower subsidies for adoption of abatement practices (including cropping system changes), and constraints or taxes on nitrogen or water use. Pfeiffer (1976) combined model-farm estimates with a hydrologic model for the Yakima River Basin, and looked at river-quality effects of various pollution-abatement procedures. His estimates demonstrated the difficulty of extrapolating from edge-of-field losses to receiving stream gains, because of nitrogen utilization by drainage ditch weeds and aquatic organisms, and sediment deposition in drainage ditches, sediment ponds, and/or small lakes between the edge of the field and receiving waters.

The Appendix contains tabular data required for sediment and nutrient loss estimates, and economic appraisals, for the Magic Valley area of Idaho and the Umatilla area of Oregon.

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EPA-287 (Cin.)
(4-76)

SECTION 1

INTRODUCTION

In October of 1972, the U.S. Congress passed Public Law (PL) 92-500, the "Federal Water Pollution Control Act Amendments of 1972." The most immediate concerns of this legislation were obvious point source discharges of municipal and industrial wastes. On a more gradual time scale, however, focus was also to be directed at point source and nonpoint source urban, rural and agricultural discharges. Initial emphasis in the point source agricultural area was given to livestock and dairy operations, and to clearly defined irrigation return flows. Permits were to be required for each such discharge. Litigation concerning the minimum size of irrigated unit requiring a permit delayed implementation of point source controls for irrigated areas, however. Subsequently, the Clean Water Act of 1977 (PL 95-217) completely exempted irrigation return flows from the National Pollutant Discharge Elimination System (NPDES) permits and placed them directly within the responsibility of Section 208 (b), the area-wide waste treatment management planning process, to be administered by the planning agencies of each state.

Planning for the control of nonpoint source discharges from irrigated and nonirrigated agricultural lands is well underway throughout the Pacific Northwest. Such planning, as required by Section 208 of the Water Pollution Control Act Amendments, is being conducted in most cases under the auspices of county or irrigation district water quality committees. One purpose of this report is to assemble and disseminate information for use by local groups in evaluating the extent to which adoption of specific management practices should decrease the discharge of sediment and fertilizer nutrients (particularly nitrogen and phosphorus) from irrigated areas of the Pacific Northwest. An equally important purpose is to provide local planning groups with a procedure for use in evaluating the economic costs of management practice changes, so that such groups can begin to address the question of how such costs should be borne for a given degree of water quality pollution control.

Personnel from the Agricultural Research Center at Washington State University have been heavily involved for several years in water quality assessment and in evaluating

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EPA-287 (Cin.)
(4-76)

economic constraints on water quality control. A detailed survey of nitrogen, phosphorus and sediment discharge from the Palouse dryland wheat region was conducted in 1969-1971 (Johnson et al., 1973; Carlile and McNeal, 1974). A salt and nutrient balance was conducted in 1970-1971 for the Wapato Project in the Yakima Valley (Nelson and Weaver, 1971), and compared to results for the same area in 1940-1941. This study was of particular value because it provided corresponding data for a typical Pacific Northwest irrigated setting before and after commercial fertilizers had been introduced and used extensively. Effects of selected management practices on nitrate leaching from irrigated soils of the Columbia Basin were evaluated during the period 1970-1974 (McNeal et al., 1977). Concurrently, economic models were being constructed, and economic evaluations of selected management practices were being made, in order to determine the cost per unit of water quality pollution control (Gossett and Whittlesey, 1976; Pfeiffer and Whittlesey, 1976). Such work, coupled with important on-going research on water quality in other Northwest states (Carter et al., 1971, 1974; Fitzsimmons et al., 1978), has produced a timely need to compile available information for use by local water quality (Section 208) planning committees. Objectives of the current project have been to:

1. Assemble, refine and present to key personnel from the Pacific Northwest a predictive procedure for estimating sediment and fertilizer nutrient losses from irrigated portions of the area.

2. Present analyses demonstrating basic approaches and typical results when assessing the economic consequences of adopting selected pollutant control practices.

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SECTION 2

CONCLUSIONS

Though considerable variation exists between physiographic regions, Pacific Northwest irrigated croplands have continued to grow relatively large amounts of hay, pasture, and small grains. These crops are relatively nonerosive and also have relatively low potentials for nitrate leaching, except for the initial plow-out period of alfalfa fields. The greatest potential for soil and nutrient losses is associated with smaller amounts of furrow-irrigated, row-crop acreage (potatoes, corn, beans, etc.) Highly erosive conditions also exist on some orchard lands of the region, if cover crops are not being used. Despite rapid conversion to sprinkler (especially center-pivot) systems, furrow irrigation remains the dominant irrigation technique for most Pacific Northwest areas.

The technique used to estimate sediment (with associated phosphorus) losses from furrow-irrigated croplands of the Pacific Northwest consists of establishing base-level conditions, with associated sediment loss, then modifying sediment-loss predictions as physical factors (slope, soil texture, crop type, stream size or percent runoff, etc.) are changed for other areas or different management conditions. Total phosphorus is assumed to remain a constant proportion of eroded sediment. Though overly simplistic, the technique at least provides a framework with which to compare additional sediment loss values as they become available, and through which needs for refinement of the effects of various physical factors should become apparent.

Nitrate leaching estimates generated for well-characterized southern California conditions were modified for the Pacific Northwest, by incorporating an estimate of the nonuniformity of water application and a soil texture-dependent denitrification multiplier. Such refinement lowered the southern California estimates, which were two- to three-fold too large when applied directly to Pacific Northwest irrigated tracts, to more realistic levels.

Physical models of nutrient loss from irrigated croplands have been coupled to economic appraisals through a model-farm approach. Use of such an approach for three Pacific Northwest

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

irrigated areas (the Magic Valley area, Idaho; the Umatilla area, Oregon; and the Yakima Valley, Washington) demonstrates the effectiveness and associated costs of selected pollution-abatement practices. For example, a substantial amount of nitrogen-loss abatement, 50 percent or more, can be achieved without significantly affecting farm income. Almost complete sediment-loss abatement can also be achieved at costs considerably below those of conversion to center-pivot sprinkler systems, an option which is being adopted with increasing frequency throughout the irrigated West. It becomes very costly to achieve nitrogen-loss abatement levels beyond 50 percent, however, or beyond those that can be achieved with managerial improvements, inexpensive shifts in existing irrigation systems, and sediment retention devices. The last increments of combined abatement, and particularly of nitrogen-loss abatement, are achieved only at extremely high cost.

Control practices to abate sediment losses will generally have little effect on the abatement of nitrogen losses. In order to simultaneously achieve the abatement of pollution from percolated and runoff waters, it is necessary to invest in more expensive irrigation systems and/or to change to substantially less profitable cropping patterns. The final choice of pollution control practices must be governed by the problem(s) to be solved and the available funds for pollution abatement. There is little reason to make expenditures for pollution abatement that substantially exceed derived benefits.

It must be recognized that edge-of-field nutrient losses cannot be translated directly to surface-stream water quality impairment. Sediments and phosphorus may be retained in drainage ditches and/or redeposited on other cropland. Nitrogen may be utilized by drainage-ditch vegetation or by other crops during return-flow reuse. Such redistribution of sediments and nutrients must be included in basin-wide models of surface-stream quality.

This study only illustrates a methodology that can be followed in arriving at pollution abatement solutions for irrigation return flows. Each problem area must be analyzed for its own characteristics, with specific agronomic, soils, and economic data collected and alternative control practices analyzed for efficiency and effectiveness in abating pollution. Choices must be made regarding the level of abatement to be achieved and the distribution of costs for such abatement.

It generally will be easier to share costs incurred for capital investments in items such as new irrigation systems or ditch lining, for public investment in capital items is generally assured of a long-term change in levels of pollution. An expenditure for implementing an irrigation scheduling service or an end-of-field filter strip, however, has no assured

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

effectiveness beyond the year of investment. If the objective of federal subsidies is to compensate the farmer for income losses, year-to-year variations in farm income due to changes in crop prices or yields can raise sizeable uncertainties about required expenditures.

This study has shown that the most cost-effective measures of pollution abatement are those of a temporary or nonstructural nature. These temporary measures will be difficult to administer, however. In the past, agencies such as the Soil Conservation Service have been reluctant to share costs of nonpermanent soil conservation practices.

These and other problems must be solved before widespread pollution abatement programs can be implemented for irrigated agriculture. This report provides a current estimate of technical knowledge and abatement alternatives which can be applied to problems of return-flow pollution. Knowledge will change as experience is gained. The information herein is only a suggested foundation on which to build.

EPA-287 (Cin.)
(4-76)

SECTION 3

RECOMMENDATIONS

This study has illustrated a methodology for assessing the costs and benefits of selected pollution abatement practices for irrigation return flows. The methodology has intentionally been kept simple to permit its usage and/or visualization by relatively nontechnical groups. It is hoped that this report will encourage prior assessment of proposed management changes by Section 208 (PL 92-500) personnel in order to quantify probable abatement and cost effects of planning efforts.

Management plans should be developed with a specific view toward the elements to be abated and the desired level of abatement to be achieved. It is not useful to abate pollutants unless derived benefits equal or exceed incurred costs. This report shows that modest levels of nutrient and sediment losses can be abated rather inexpensively through management improvements or small capital expenditures. These approaches should be considered prior to employment of more effective, but more costly or energy-intensive, irrigation systems. Expensive and energy-intensive sprinkler systems should not be subsidized for abating nitrate losses, for example, if realistic management of fertilizer and water with present furrow-irrigation systems can achieve adequate abatement. On the other hand, it occasionally will be necessary to turn to a practice that is more expensive and less energy-intensive than others in abating a single pollutant, because of its combined effectiveness in abating more than one pollutant, such as leached nutrients and eroded sediments.

Abatement plans should emphasize education programs that will inform parties about their potential role in environmental improvement. It is expected that significant quality improvements can be achieved by some farmers without costly investments or reductions in net income. These efforts should be emphasized and implemented prior to the use of subsidy programs that may also affect subsequent freedom of decision making.

This study primarily provides an assessment of current knowledge for estimating effluent quantities and evaluating alternative abatement control measures. To achieve the desired level of generality for this report, data specific to all major

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

irrigated regions of the Pacific Northwest could not be included. Hence, the data presented are intended only as a foundation upon which to build in solving problems for a particular region. Similarly, the methodology suggested for project assessment is only an example of that which might be useful or necessary in any specific situation. It is recommended that persons responsible for pollution abatement planning obtain the assistance of professional scientists (particularly in the areas of soils, agricultural engineering, and agricultural economics) to help build and evaluate alternative programs. The costs of such assistance are likely to be far less than the costs of programs improperly perceived and implemented.

Finally, it is recommended that abatement programs be developed with a careful view of the problems to be solved and the benefits to be derived from such resolution. It is not useful to expend scarce capital or to reduce agricultural outputs merely to reduce effluents that are causing virtually no problem. Similarly, there is no reason to expend large sums to abate one component, such as nitrates, if another such as water temperature is really limiting the quality of receiving waters. We must not focus on the abatement of one effluent simply because we know how to reduce its level, if other pollutants actually limit water quality. In short, we must be careful not to allow the level of program costs to escalate beyond the level of perceived and measurable program benefits.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

SECTION 4

PHYSICAL DATA FOR SELECTED PHYSIOGRAPHIC REGIONS

Much of the information required for pollution abatement planning should come from precise research data, including probable cropping patterns, crop water requirements and nutrient needs, probable irrigation systems for various crop/soil combinations, and water quantity and water quality data (including diversions and return flows). The required data generally are not available in anything approaching complete form, however, even for a single irrigated area. Their existence for all regions, crops and irrigation systems of concern to Pacific Northwest agriculture is still probably decades away. Research has recently been conducted on some of the more important aspects mentioned above (King et al., 1977; Fitzsimmons et al., 1978), but research on other important aspects has not even begun.

Current and historical cropping patterns for typical irrigated areas of the Pacific Northwest provide an insight into anticipated crop production trends. Such data may also be used to predict overall fertilizer usage, probable tillage practices, and even crude nutrient-loss estimates. Boundaries of irrigation projects and of principal physiographic areas rarely follow political (state and county) lines, though cropping data from the most readily-available source, the Census of Agriculture, are based upon state and county units. Precise data from local crop inventory services should be used for specific planning or implementation programs. Census of Agriculture figures for the 1974 crop year have been used in this report, but only for illustrative purposes.

Fertilization rates should be governed by actual uptake rates of major nutrients (i.e., nitrogen, phosphorus and potassium) by various crop plants. Data on crop nutrient requirements are generally available from the research literature for the main crops grown in the Pacific Northwest, as well as from fertilizer guides provided by the state agricultural experiment stations. Actual rates of fertilization commonly used for specific crops in the various physiographic areas are not known, however. The difference between theory and practice remains largely an unknown, except for qualitative impressions conveyed by soil and crop experts from the region.

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EPA-287 (Cin.)
(4-76)

Different crops have differing water requirements. Estimates of crop water requirements are available from the literature. Combining crop water requirements with data on the amounts of water being diverted for irrigation provides an insight into the relative efficiency of water use. The data can thus be used to index total amounts of runoff plus deep percolation. Such water losses provide the main mechanism for sediment and nutrient removal during irrigation. Overall data on the types of irrigation systems currently being used in the region are available for most of the physiographic areas (e.g., the excellent report of King et al., 1977), though such data rarely distinguish the types of land (e.g., land capability classes, or soil textural and slope classes) being irrigated with each type of system. Soil survey reports and land classification data could be used in some cases to estimate the types of irrigation systems which should be most efficient in controlling sediment and fertilizer nutrient losses from a given area.

The quantities and qualities of irrigation return flows for the various physiographic units should provide excellent integrated estimates of the pollution potential from sediments and fertilizer nutrients under "real-world" operating conditions. Data on return flows in the Pacific Northwest are quite limited, however, and are confined in general to a few highly-studied areas (Nelson and Weaver, 1971; Carter et al., 1971, 1974; Fitzsimmons et al., 1978). Even in these cases there are generally insufficient data to permit precise correlations of water quality with cropping patterns, water application rates and methods, soil type and slope, fertilization rates, etc.

Because of the limited data base, the approach of this study has been to compile typical information on irrigation, cropping and fertilization practices for the tri-state area, and to utilize these data in simple physical and economic models in order to illustrate appropriate methodology for estimating sediment and nutrient losses, with associated economic costs. Inputs have been sought from state, federal, and private industry personnel of the region, including inputs from a cross-section of such personnel during a "Nutrient Loss Workshop" held in Pullman, Washington, early May of 1978. Because of the diversity of opinions expressed during such interactions, however, no consensus as to "best-available" approaches for nutrient loss estimates has been reached. The viewpoints in this report represent the considered judgments of its authors alone.

PHYSIOGRAPHIC AREAS SELECTED FOR STUDY

Each state of the Pacific Northwest has been divided into a number of physiographic areas for the purposes of this study. The cropped acreage of each area is compared to the total irrigated acreage of the state. This may be useful to insure that

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EPA-287 (Cin.)
(4-76)

each major region and crop is represented if a plan is to be state-wide in scope. As an example, principle physiographic areas for each of the three states, representing three-fourths or more of the total irrigated acreage and all major crops grown within the state, are delineated below.

Washington

Principal irrigated physiographic areas delineated for the state of Washington include the Columbia Basin (in Grant, Franklin, Adams and Lincoln counties), the Yakima area (in Yakima, Kittitas and Benton counties), the Okanogan area (in Okanogan, Chelan and Douglas counties), and the Walla Walla area (in Walla Walla and Columbia counties). These four areas constituted 81 percent of the total irrigated area of the state [1,309,018 acres or 530,200 hectares (ha)][1] in 1974.

Oregon

Principal irrigated areas for the state of Oregon include the Lake-Harney area (including portions of Lake and Harney counties), the Ontario area (in Malheur county), the Klamath Falls area (in Klamath county), the Willamette Valley (in Marion, Lane, Linn, Yamhill, Polk, Washington, Benton, Clackamas and Multnomah counties), the Madras area (in Crook, Jefferson and Deschutes counties), the Baker area (in Baker and Union counties) and the Hermiston area (in Morrow and Umatilla counties). These seven areas constituted 84 percent of the total irrigated area (1,561,438 acres or 632,400 ha) of Oregon in 1974.

Idaho

Principal irrigated areas for the state of Idaho include the Snake River Plains area (in Twin Falls, Cassia, Minidoka, Jerome, Gooding, Caribou, Power, Bannock, Lincoln and Blaine counties), the Idaho Falls area (in Bingham, Jefferson, Bonneville, Madison, Fremont, and Teton counties) and the Boise Valley (in Canyon, Ada, Elmore, Payette, Gem and Washington counties). These three areas constituted 73 percent of the total irrigated area of Idaho (2,859,047 acres or 1,158,000 ha) in 1974.

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[1] English units have been used as the standard of expression throughout this report, to enhance utility for local water quality (e.g., Section 208) planning and implementation personnel. Metric equivalents have been provided as well, with a table of English/metric conversion factors included on page xii.

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EPA-287 (Cin.)
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CROP PRODUCTION PATTERNS

Crop production patterns for the physiographic areas described above are presented in Tables 1-4. Nearly 70 percent of the irrigated acreage for the tri-state region in 1974 was in pasture, hay (or hay seed crops), and small grains, Table 1. Such crops are of relatively low value, but also represent cropping situations which produce minimal sediment erosion and fertilizer nutrient leaching, because of the relatively small amounts of fertilizer applied and because of their close-growing nature. The greatest overall pollution potential is probably associated with the 20 to 25 percent of the land cropped to potatoes, sugarbeets, field corn, vegetables, and similar crops. Tree-fruit areas, although often on highly-erosive land, are commonly maintained in grass or legume cover crops. Hence, the proportion of the time that orchard soils are bare (and subject to significant erosion) is often minimal. Tree fruits are also fertilized and irrigated at lesser rates than common vegetable crops, and are more deeply rooted, so the potential for nutrient (nitrate) leaching is minimized.

Included at the bottom of Table 1 are corresponding cropped acreage estimates for 1975 from a report by King et al. (1977) dealing with irrigation development in the Pacific Northwest. State-wide totals differ substantially from Census of Agriculture figures for 1974, and relatively little of the difference can be attributed to the one-year difference in reporting periods. Much of the difference is due to differences in census base, for the Census of Agriculture figures are tied to owner residence patterns, rather than to actual county-by-county acreage figures. There appears to exist considerably more absentee land ownership for Idaho (where the King et al. state-wide total was 35 percent greater than the Census of Agriculture total) than for Washington or Oregon (where the King et al. state-wide totals were only 22 percent and 19 percent greater, respectively). The percentage of the total regional irrigated area represented by the irrigated area of each state was within 1 percent to 3 percent for the two data sources, however. Overall trends remained essentially the same no matter which set of figures were employed for the calculations, as long as percentages were used in place of actual acreages.

Washington

State-wide Trends--

Cropping patterns in 1974 for the state of Washington indicated 10 percent less irrigated land in pasture, hay and hay seed, and small grains than the tri-state average, whereas nearly 30 percent of the cropland of the state was in potatoes, sugarbeets, field corn, vegetables and similar crops. The extensive tree-fruit region contributed nearly 11 percent of the irrigated area of the state in 1974. Overall, the state

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TABLE 1. PACIFIC NORTHWEST (1974) IRRIGATED ACREAGE, BY CROP AND STATE (CENSUS OF AGRICULTURE FIGURES)

Crop	WA	OR	ID	Overall
	- (% of state total) -			(%)
Pasture	8.9	21.0	13.5	14.5
Hay & hay seed	25.8	41.5	31.1	32.8
Small grains	24.0	13.5	27.4	21.6
Potatoes	6.8	3.5	10.9	7.1
Sugarbeets	4.7	1.0	3.1	2.9
Field corn	3.6	2.1	3.9	3.2
Vegetables	5.5	7.1	1.3	4.6
Tree fruits	10.9	2.3	0.3	4.5
Other crops	11.4	8.0	9.8	9.7
% of state or area total[a]	101.6	100.0	101.3	100.9
1974 irrigated area[b] (acres)[c]	1,309,018	1,561,438	2,859,047	5,729,503
% of regional total	22.8	27.3	49.9	100.0

[a] Some totals exceed 100% due to rounding errors.

[b] Corresponding 1975 totals from King, et al. (1977): Washington--1,594,457 acres; Oregon--1,850,660 acres; Idaho--3,845,651 acres; total--7,290,768 acres.

[c] 1 acre = 0.405 hectare.

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(4-76)

TABLE 2. WASHINGTON (1974) IRRIGATED ACREAGE, BY CROP AND PHYSIOGRAPHIC AREA (CENSUS OF AGRICULTURE FIGURES)

Crop	Columbia Basin	Yakima Area	Okanogan Area	Walla Walla Area	Total acreage	Percent of state crop total[a]
	(thousands of acres)[b]					
Pasture	22.5	58.8	4.6	5.9	91.8	78.7
Hay & hay seed						
Alfalfa hay	138.7	40.7	17.1	13.3	209.8	88.5
Clover/grass hay	2.2	17.0	1.1	2.3	22.6	61.1
Alfalfa seed	15.0	4.7	0.0	10.7	30.4	98.2
Small grain						
Winter wheat	195.5	58.0	8.7	24.5	286.7	96.0
Barley	4.2	3.9	0.0	1.6	9.7	78.9
Potatoes	60.2	21.3	0.1	4.6	86.2	96.6
Sugarbeets	40.0	18.1	0.5	4.1	62.7	100.0
Field corn	22.8	17.7	0.6	0.6	41.7	87.5
Vegetables						
Sweet corn	9.8	16.9	0.0	0.4	27.1	89.6
Dry peas	18.9	0.0	0.0	1.0	19.9	100.0
Asparagus	2.2	10.3	0.0	7.4	19.9	100.0
Tree fruits						
Apples	3.0	50.1	44.8	0.3	98.2	100.0
Pears	0.3	10.3	7.5	0.0	18.1	94.3
Other crops						
Hops	0.0	22.4	0.0	0.0	22.4	100.0
Mint	1.7	16.6	0.0	0.0	18.3	95.3
Total acreage reported above	537.0	366.8	85.0	76.7	1,065.5	
Above as percent of area's total	92.5	88.6	91.7	89.4	90.9	
Total acreage reported for area	580.3	413.9	92.7	85.8	1,172.7	
Area as percent of state's total	44.3	31.6	7.1	6.6		89.6

[a] Percent of irrigated acreage accounted for by these crops statewide = 88.7.

[b] 1 acre = 0.405 hectare.

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TABLE 3. OREGON (1974) IRRIGATED ACREAGE, BY CROP AND PHYSIOGRAPHIC AREA (CENSUS OF AGRICULTURE FIGURES)

Crop	Lake-Harney Area	Ontario Area	Klamath Falls Area	Willamette Valley	Madras Area	Baker Area	Hermiston Area	Total acreage	Percent of state crop total[a]
	- - - - - - - - -	- - - - - - - - -	- - - - - - - - -	-(thousands	of acres)[b]-	- - - - - - - - -	- - - - - - - - -	- - - - - - - - -	
Pasture	69.1	24.1	48.2	15.1	35.6	54.0	18.5	264.6	80.7
Hay & hay seed:									
Alfalfa hay	37.2	51.0	34.9	7.8	27.5	38.9	32.5	229.8	87.0
Other hay	140.7	36.9	26.2	15.3	18.9	34.4	4.6	277.0	71.8
Alfalfa seed	0.0	9.6	0.0	0.0	0.0	0.0	6.6	16.2	114.9
Other seed	0.0	0.1	0.0	6.5	9.3	5.6	0.0	21.5	69.3
Small grains:									
Winter wheat	10.8	15.3	10.6	8.0	21.1	14.7	44.5	125.0	100.5
Barley	31.1	13.9	29.5	1.2	1.2	5.6	2.6	85.1	101.2
Other grains	20.8	2.2	20.3	0.6	0.3	0.4	0.0	44.6	100.0
Potatoes	11.2	13.1	11.2	1.3	5.5	0.9	17.4	60.6	109.9
Sugarbeets	0.0	12.0	0.0	0.7	0.0	0.0	2.0	14.7	101.4
Field corn	0.1	13.1	0.1	8.5	0.8	1.3	6.1	30.2	92.6
Vegetables:									
Sweet corn	0.0	4.7	0.0	35.5	0.0	0.0	0.3	40.5	98.4
Green peas & beans	0.0	0.0	0.0	1.3	0.0	0.5	5.1	6.9	109.8
Other vegetables	0.0	7.3	0.0	52.6	0.0	0.0	2.6	62.5	98.9
Tree fruits:									
Pears	0.0	0.0	0.0	0.5	0.0	0.0	1.3	1.8	
Peaches & plums	0.0	0.0	0.0	1.6	0.0	0.0	0.7	2.3	115.0
Cherries	0.0	0.0	0.0	9.1	0.0	0.0	3.9	13.0	76.5
Other crops:									
Mint	0.0	3.1	0.0	15.9	15.0	0.0	1.3	35.3	97.2
Strawberries	0.0	0.0	0.0	4.0	0.0	0.0	0.0	4.0	94.2
Total acreage reported above	321.0	206.1	181.0	185.5	135.2	156.3	150.0	1,335.4	
Above as percent of area's total	121.7	98.4	99.2	89.8	97.8	98.2	100.0	101.9	
Total acreage reported for area	263.7	209.8	182.5	206.6	138.3	159.1	150.0	1,310.0	
Area as percent of state's total	17.5	13.9	12.1	13.7	9.2	10.6	9.9		83.9

[a] Percent of irrigated acreage accounted for by these crops statewide = 99.0 percent.
[b] 1 acre = 0.405 hectare.

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TABLE 4. IDAHO (1974) IRRIGATED ACREAGE, BY CROP AND PHYSIOGRAPHIC AREA
(CENSUS OF AGRICULTURE FIGURES)

Crop	Snake River Plains	Idaho Falls Area	Boise Valley	Total acreage	Percent of state crop total a/
	(thousands of acres) a/				
Pasture	105.4	85.7	65.3	256.4	78.6
Hay & hay seed					
Alfalfa hay	268.0	183.6	101.0	552.6	78.8
Alfalfa seed	2.8	0.4	17.4	20.6	74.0
Small grains					
Winter wheat	194.2	158.0	54.5	406.7	93.2
Barley	117.6	95.2	43.7	256.5	85.6
Other grains	21.6	9.2	55.2	86.0	100.0
Potatoes	110.0	155.5	28.9	294.4	94.8
Sugarbeets	43.5	9.1	29.5	82.1	92.1
Field corn	42.3	7.4	45.7	95.4	86.6
Dry beans	122.7	0.9	14.2	137.8	96.6
Total acreage reported above	1,028.1	705.0	455.4	2,188.5	
Above as percent of area's total	91.1	96.7	96.3	94.3	
Total acreage reported for area	1,118.2	729.3	472.6	2,320.1	
Area as percent of state's total	39.9	26.0	16.9		73.3

a/ Percent of irrigated acreage accounted for by these crops statewide = 88.5 percent.

b/ 1 acre = 0.405 hectare.

appeared to offer a somewhat greater potential for erosional and leaching losses of fertilizer nutrients from irrigated croplands than did other Pacific Northwest states.

Major Washington Physiographic Areas--

Of the 1974 irrigated area of Washington, 69 percent was located in the Columbia Basin and Yakima Valley (Table 2). The Okanogan area (predominantly a tree-fruit region) and the Walla Walla area each contributed approximately 7 percent to the total for the state. Nearly 14 percent of the irrigated area in the Yakima Valley was in pasture, with much of this in Kittitas County, along the upper reaches of the Yakima River. A combination of fine-textured and poorly-drained soils in this area produces relatively wet lands, for which irrigated pasture is a logical cropping choice. The Yakima Valley and the Okanogan area each had lesser amounts of irrigated hay, hay seed, and small grains than did the other two physiographic areas.

Over 10 percent of the land in the Columbia Basin was devoted to the growth of potatoes (significantly above the statewide average) and nearly 7 percent of the land in this area was devoted to sugarbeets. Each of these crops is grown under highly erosive conditions, with sizeable nutrient losses, under normal conditions. All sugarbeet production in Washington and Oregon has recently been eliminated due to closure of processing facilities, however. The Walla Walla area had the highest proportion of irrigated vegetable production, with over 10 percent of the land in this category. Field corn was primarily concentrated in the Columbia Basin and the Yakima Valley. Nearly 15 percent of the land in the Yakima area, and 56 percent of the land in the Okanogan area, was devoted to tree-fruits in 1974. Hops and mint were also prominant crops for the Yakima area.

The crops listed contributed 89 percent or more of the total irrigated acreage for the respective physiographic areas in 1974. In addition, the four physiographic areas contributed 88 percent or more of the total acreage in the state devoted to each crop, with the exception of clover-grass hay (which is grown extensively in western Washington) and pasture and barley (which are distributed throughout the remainder of the state). The state of Washington had only 23 percent of the total irrigated acreage for the tri-state area in 1974.

The irrigated acreage in the Columbia Basin project increased steadily from 1959 to 1974 (data not presented) as additional irrigation blocks were brought under development by the U.S. Bureau of Reclamation and by private developers. The most dramatic crop acreage decrease during this period was in the growth of dry beans, with the greatest increases being for alfalfa hay and hay seed, winter wheat, potatoes, sugarbeets, and sweet corn. The sugarbeet acreage virtually disappeared in 1979, however. Relatively little change in irrigated acreage

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

occurred between 1959 and 1974 for the Yakima area. Changes in cropping patterns for the area during this period included decreases in acreage devoted to pasture, alfalfa hay, spring wheat, and field corn, accompanied by corresponding increases for winter wheat, potatoes, sweet corn, and mint. Little change was evident in Okanogan area cropping patterns with time, except for a substantial increase in the acreage of irrigated winter wheat in Douglas County. The acreage of irrigated cropland reported for the Walla Walla area more than doubled over the 1959-1974 period, with most of the change being due to sizeable increases in winter wheat, asparagus, and alfalfa seed production.

Oregon

State-wide Trends--

Irrigated lands of Oregon represented 27 percent of the total irrigated area for the Pacific Northwest in 1974 (Table 1). Approximately 76 percent of this land was in pasture, hay and hay seed, and small grain production, with only 16 percent in potatoes, sugarbeets, field corn, vegetables, and "other" crops. The tree-fruit acreage of Oregon was substantially smaller than that of Washington. As most of the tree fruit of the state was not located in one of the selected physiographic areas, its acreage will not be detailed below.

Major Oregon Physiographic Areas--

The listed physiographic areas contributed approximately three-fourths of the 1974 irrigated acreage of Oregon (Table 3). The most rapidly-growing area was near Hermiston in northeastern Oregon, where large numbers of center-pivot irrigation systems have been installed in recent years on soils that were formerly regarded as too sandy for irrigation. This area is being developed from shallow wells or with Columbia River water. Similar trends are evident across the river in Washington, on the lower elevations of the Horse Heaven Hills. The proportion of irrigated acreage in the Willamette Valley may be somewhat misleading, for much of this irrigation is on a supplemental basis, to augment water stored in soil profiles during the extremely wet winters (averaging approximately 40 inches of rainfall) in this area. For short-season crops or for cases where adequate soil profile water storage capacity exists, no supplemental irrigation is necessary.

The proportion of irrigated pasture was highest for the Klamath Falls and Baker areas, where shallow water tables and/or shallow and stony soils are common. It was lowest for the Ontario and Willamette Valley areas. Although the Lake-Harney area represented the largest physiographic area of Oregon, 77 percent of this acreage was devoted to hay and pasture in 1974. A substantial portion of the total for the Willamette Valley was in the "other seed" (other than alfalfa) category. This is one

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PAGE NUMBER

EPA-287 (Cin.)
(4-76)

of the major grass-seed production areas of the nation. The largest amounts of small grain production in Oregon in 1974 were in the Lake-Harney, Klamath Falls, and Hermiston areas.

Major potato-growing regions were the Hermiston, Ontario, Klamath Falls and Lake-Harney areas. The Ontario area also represented virtually all of the sugarbeet acreage of the state and a significant proportion of its field corn, vegetable and mint acreage. A sizeable amount of field corn and vegetables was planted in the Hermiston area as well in 1974. Nearly 58 percent of the land in the Willamette Valley was devoted to the growth of potatoes, corn, vegetables and "other" (generally intensive) crops, making this area particularly susceptible to leaching and erosional losses of fertilizer nutrients.

More than 80 percent of the state crop total for 1974 was grown in the listed physiographic areas, except for hay and hay seed crops other than alfalfa, and for tree fruits such as cherries and pears. The crops listed accounted for 95 to 100 percent of the total irrigated acreage in each physiographic area. Values greater than 100 percent probably reflect uncertainties as to what constitutes "irrigated" acreage in some of the settings of eastern Oregon, and/or a mix of figures for crops grown both under irrigated and dryland conditions.

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Total irrigated acreage of the Klamath Falls area decreased significantly between 1959 and 1974 (data not presented), whereas it remained virtually constant for the Ontario area. Irrigated acreage increased with time during this period for each of the other areas, and particularly for the Hermiston area. The Lake-Harney area evidenced a substantial increase in small grains and potatoes between 1959 and 1974. A major trend for the Ontario area was an increase in winter wheat and barley acreage, and a decrease in spring wheat acreage, over the 15-year period. Corresponding trends in crop acreage for the Klamath Falls area were an increase in winter wheat acreage and a decrease in acreage devoted to other grains and to pasture. A substantial increase in acreage of irrigated land in the Willamette Valley between 1959 and 1974 probably reflected fairly widespread adoption of supplemental irrigation to insure crop production during the hot, dry summers common to this area. Increased crop acreage in this area was primarily devoted to hay seed other than alfalfa, winter wheat, sweet corn, and mint. The mint acreage appeared to have peaked around 1969, probably because of increasing disease problems in long-term mint production areas. No reason was apparent for the sizeable decrease in peach and plum acreage of this area between 1969 and 1974. Major increases in irrigated acreage for the Madras area over the 15-year period were in the production of seed crops other than alfalfa, winter wheat, and mint. Part of the mint acreage from the Willamette Valley had been moved to this area because of the above-mentioned disease problems. There also appeared to

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

have been a sizeable increase in irrigated pasture acreage between 1959 and 1969 for this area and the Baker area. Such a trend is surprising, for most physiographic areas appeared to have been declining in irrigated pasture acreage during the same period. Substantial changes in cropping patterns for the Hermiston area by 1974 included large increases in wheat and potato acreage, and moderate increases in alfalfa seed, green pea, and tree fruit acreage as well. Potatoes are one of the more popular crops for the center-pivot irrigation systems which have been used to develop the more sandy soils of this area in recent years.

Idaho

Statewide-Trends--

The state of Idaho represented approximately one-half of the irrigated acreage in the Pacific Northwest during 1974. Major trends for Idaho irrigated agriculture (Table 1) included 9 percent more land in small grain production than averages for Washington and Oregon, and over 5 percent more land in potato production. The proportions of irrigated acreage devoted to vegetables and to tree fruits, however, were considerably smaller for Idaho than for either of the other Pacific Northwest states.

Major Idaho Physiographic Areas--

Three physiographic areas represented over 70 percent of the irrigated crop acreage of Idaho in 1974 (Table 4). Of the three areas, the Boise Valley had the lowest proportion of land in irrigated pasture, and the highest proportion devoted to field corn production. The Idaho Falls area had the greatest proportion of land devoted to potato production, whereas the Snake River Plains had the greatest proportion of irrigated pasture, hay and hay seed, small grain, sugarbeet, and dry bean production. The percentages of acreage in the Snake River Plains, Idaho Falls area and Boise Valley devoted to highly erosive (row) crops were 28 percent, 24 percent, and 25 percent, respectively. The three physiographic areas represented over 80 percent of the crop totals for each of the crops listed in Table 4, with the exception of pasture, alfalfa hay, and alfalfa seed production.

Major changes in crop distribution patterns within the Snake River Plains area during the period 1959 to 1974 (data not presented) included pronounced increases in acreages of winter wheat, barley, and potatoes, and a substantial decrease in acreage of irrigated pasture and other grains. Total irrigated acreage remained relatively constant over this period. Some additional acreage was apparently put under production in the Idaho Falls area, with major changes in crop distribution patterns including increased acreage devoted to winter wheat, barley and potatoes, and decreased acreage devoted to the production of other grains. Major changes for the Boise Valley

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

included increased acreage devoted to alfalfa seed, barley, and potatoes, with decreased acreage being devoted to the production of pasture and other hay seed.

Summary

The cropping pattern information presented above should orient the reader to relative characteristics of selected Pacific Northwest physiographic regions. Localized cropping pattern data should be used for specific water quality planning purposes, however. The information in this section may prove useful in deciding with what degree of validity water quality information can be extrapolated from one Pacific Northwest physiographic area to another.

DISTRIBUTION OF IRRIGATION SYSTEMS

Distribution of irrigation systems among 1975 Pacific Northwest irrigated acreage is summarized in Table 5. These data have been summarized from a report by King et al. (1977). Gravity (furrow) irrigation systems predominated in the tri-state area, averaging nearly 56 percent of the 1975 irrigated acreage. They constituted about 40 percent of the irrigated acreage of Washington, but nearly 65 percent of the Idaho total. Because of the highly erosive and nonuniform nature of this form of irrigation, it is the most environmentally hazardous of the types listed with respect to sediment, phosphorus and nitrogen losses from irrigated croplands.

Though some types of sprinkler systems can lead to appreciable localized erosion (as at the periphery of center-pivot sprinkler patterns or when big-gun sprinklers are used for irrigation during periods of incomplete crop canopy cover), the amounts of sediment and phosphorus actually eroded from sprinkler-irrigated fields are generally assumed to be negligible. The major losses of pollutants from such systems arise instead from leaching of nitrogen and mobile pesticides due to nonuniformity in sprinkler application patterns. In addition to system design problems, sprinkler-irrigated fields in the Pacific Northwest often suffer systematic wind distortion due to prevailing local wind patterns. Most of the new land being developed in the region is sprinkler-irrigated, with center-pivot systems being particularly popular because of their minimal labor requirements. In addition, much gravity-irrigated acreage is being converted to sprinkler systems. The main deterrents to such trends in the future may be increased energy costs or even a lack of adequate energy availability for new sprinkler system installations.

The amount of drip-irrigated acreage in the Pacific Northwest is low at present, and likely to remain so for the fore-

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(4-76)

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TABLE 5. DISTRIBUTION OF IRRIGATION SYSTEMS AMONG PACIFIC NORTHWEST IRRIGATED ACREAGE, 1975 (KING, ET AL.)

System	WA	OR	ID	Overall
	- (% of state total) -			(%)
Gravity	41.0	51.5	63.9	55.7
Hand-move sprinkler	12.6	21.9	21.0	19.4
Side-roll sprinkler	26.1	18.0	8.6	14.8
Center-pivot sprinkler	12.6	5.5	4.7	6.6
Solid-set sprinkler	1.9	1.4	1.8	1.7
Permanent sprinkler	4.8	0.6	0.01	1.2
Big-gun sprinkler	0.8	1.6	0.04	0.6
Drip	0.2	0.01	---	0.05
% of state or area total	100.0	100.5	100.1	100.1
1975 irrigated area (acres)[a]	1,594,457	1,850,660	3,845,651	7,290,768
% of regional total	21.9	25.3	52.7	99.9
Statewide or area farm water application (acre-feet/acre)	4.3	2.7	2.8	3.1

[a] 1 acre = 0.405 hectare; 1 foot = 0.305 meter.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

seeable future. An exception may occur if low-head, gravity-fed emitter systems are adopted for tree-fruit and vineyard operations. Such a trend is evident in some California areas at present.

Despite having the greatest proportion of sprinkler-irrigated acreage, Washington also had the greatest per acre water usage [4.3 acre-feet(ft)/acre or 1.31 ha-meters(m)/ha annually] according to King et al. This figure seems realistic, and agrees with per-acre figures generally quoted for the Columbia Basin project, for example. The figure for Idaho croplands seems unrealistically low, particularly when one considers the high proportion of gravity (furrow) irrigation in the state. Part of the difference may be attributed to the generally more coarse-textured soils of Washington. The Idaho figure is incompatible with much higher reported values for the Twin Falls area, however (Carter et al., 1971), and with the heavy water usage of the Idaho Falls area where much of the charging of the southern Idaho aquifer occurs. The Washington figure is more realistic for Pacific Northwest irrigated settings. The Oregon figure, though also low, is acceptable because of the supplemental nature of much of the irrigation in the Willamette Valley and the Lake-Harney physiographic areas, two of the principal irrigated regions of Oregon.

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Washington

Approximately one-third of the Columbia Basin irrigated acreage in 1975 was irrigated by gravity (furrow) systems, with most of the remainder being irrigated by side-roll or center-pivot sprinklers (King et al., 1977). A surprising aspect of the King et al. data for this area was the relatively low water use [40.9 acre-inch(in)/acre, or 104 ha-centimeter(cm)/ha)] assigned to potatoes (a crop which normally requires frequent irrigations). This suggests that a sizeable proportion of the potato acreage in this area was irrigated with center-pivot sprinkler systems. Water usage for the Yakima area was reported to be substantially greater than for the Columbia Basin, with a higher water use figure having been assigned to potatoes [57.7 acre-in/acre, or 147 ha-cm/ha]. Gravity irrigation dominated this area, reflecting the older nature of the Yakima development. No gravity irrigation systems were reported for the Okanogan area, with side-roll (for non-tree fruit lands) and permanent, hand-move and solid-set sprinkler systems dominating. For the Walla Walla area, 90 percent of the irrigation was reported to be with sprinklers. Most of these systems were of the more traditional side-roll and hand-move types, rather than center-pivot operations.

Oregon

Annual water usage for the Lake-Harney area was low (King

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

et al., 1977), despite the fact that most systems were of the gravity type. As indicated earlier, this reflects the early-season, supplemental nature of irrigation in this water-deficient portion of the state. In addition to their low water usage, the gravity-irrigated crops in this area were generally of close-growing type, and hence relatively nonerosive. Water usage for the Ontario area was also relatively low (averaging 42.2 acre-in/acre, or 107 ha-cm/ha), and more uniform between crops than for most other Pacific Northwest irrigated areas. Soil water intake rates may limit water usage throughout much of this area. Similar conclusions could be drawn for the Klamath Falls area. Annual water usage was exceptionally low for the Willamette Valley (averaging 20.4 acre-in/acre, or 51.8 ha-cm/ha), because the irrigation remained primarily supplemental in nature. Most irrigation in this area was also with less intensive sprinkler systems, such as the hand-move, side-roll or big-gun types. For the Madras area, irrigation systems were about equally distributed between gravity, side-roll and hand-move types. Most irrigation systems for the Baker area were of gravity type (on close-growing crops) or limited-intensity side-roll or hand-move systems. Most systems in the Hermiston area were of center-pivot or side-roll type, on relatively sandy soils. Water usage for this area averaged 32.6 acre-in/acre, or 82.8 ha-cm/ha.

Idaho

Particularly surprising were the relatively low water use values reported (by King et al., 1977) for potatoes in all three Idaho physiographic areas (averaging 27.0 to 34.9 acre-in/acre, or 68.6 to 88.7 ha-cm/ha), because gravity irrigation predominated in each area. Combined with hand-move sprinkler systems, these two types of systems accounted for 76 to 93 percent of the total irrigated acreage for the three regions in 1975.

LAND CAPABILITY CLASSES, SOIL TYPES, AND SLOPE CLASSES

Land capability classifications are groupings of soils that express, in a general way, the suitability of those soils for different agricultural purposes. Basic physical factors such as climate, soil type (texture), topography, and drainage are each of importance in determining the capability classification of a given soil. Economic considerations also must be included, in order to determine the cost of modifications necessary to make the soil a productive unit.

In any given area, the morphology, chemical and physical characteristics of soils are closely related to the capability of the soil for sustaining irrigated productivity. Relevant properties include soil texture and structure; bulk density;

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

pH; cation exchange capacity; sequence and thickness of horizons; and depth to caliche, basalt, gravel, or other root-limiting zones. Soil characteristics affect inherent fertility levels, irrigation methods and timing, drainage characteristics and choice of crops to be grown.

The effects of slope on soil suitability for irrigation are in turn influenced by soil erodibility, duration and intensity of local rainfall events, irrigation method, farm income potential, and types of crops to be grown. In general, an increase in slope results in a decrease in land quality for irrigation. This decrease is greater for soils of inherently unstable structure. If lands are too flat, however, productivity can be reduced because of waterlogging and poor aeration, unless adequate deep drainage exists. The decline in land quality with increase in slope is also more pronounced for surface (gravity) systems than for sprinkler systems. As slope increases, cropping patterns are frequently shifted for high-value row crops to less valuable close-growing crops. The orchard crops common to the Pacific Northwest represent a major exception to this generalization.

Information on land capability classes, soil textures, and slope classes for the Pacific Northwest physiographic areas varies a great deal. Early soil survey reports, prior to about 1940, only provide usable information on representative textures and depths of soils. Even this information is extremely qualitative. An example of a report in this category is that for Kittitas County, Washington. Soil surveys during the 1940s were somewhat more complete, with broad slope classes being provided for each soil series in addition to information on the textures and depths of major soil series from the area. Soil surveys since the early 1950s usually contain tabular information on the distribution of major soil series as a percentage of the total area surveyed, including slope classes for the major soil types (textural classes) within each soil series. Many of the reports also provide an extensive table which places the various soil series into appropriate land capability classes. The description of each soil series provides information on effective crop rooting depth and (occasionally) on the approximate extent to which the soil is being irrigated. Such information can be used for general planning and for assessment of the effects of abatement control practices on an area-wide basis. It is not sufficient for individual-farm planning.

Use of soil survey reports to obtain information appropriate for this report would be highly subjective. Hence, no attempt has been made to summarize available reports for this study. Soil survey information has been qualitatively summarized in order to provide soil texture and slope class information for model farms in the Magic Valley area of Idaho and the Umatilla area of Oregon, as part of the economic assessment of

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EPA-287 (Cin.)
(4-76)

pollution abatement practices for each area. Local water quality planning groups will need to ferret out individual-area soils information appropriate to their own settings. An appropriate starting place for such a search is the local Soil Conservation Service (SCS) office. In many cases, such data will be of substantially better quality, and of more useful scale, than published reports. The purpose of the present report is to demonstrate how such information might be used.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

SECTION 5

ECONOMIC CONCEPTS AND POLICIES RELATED TO CONTROL OF POLLUTION FROM IRRIGATED AGRICULTURE

Economic activity is the process whereby natural resources are converted into products that satisfy human needs and wants. Sometimes this is done directly, as when wind is harnessed to pump water for an isolated farmstead. At other times, it is accomplished in a more indirect way. Agriculture as an industry is heavily dependent upon the use of natural resources, both directly and indirectly. Incursion by one man on natural resources can limit the activities of others whenever resources are limited in supply. A second problem arises whenever natural endowments appear to be free. Air, sunlight, moving water, and some public lands are often regarded in this class of resources. They acquire this cost-free characteristic because they are seemingly plentiful or because it would require undue expense to harness them or to require users to pay for them. The fact that they are free has made them subject to tremendous abuse. Smoke is emitted into (free) air; sewage is dumped into (free) rivers and lakes; beer and soft drink cans are thrown on the (free) grass in the public park or roadway.

Nature lovers tend to favor natural eco-systems rather than manmade eco-systems. This preference does not necessarily result from a carefully reasoned conclusion based on the study of man and his needs. Instead, it is an article of faith, a social value judgment that may conflict with values of other people--values such as freedom, justice, material progress, health, companionship, enlightenment, and peace (Crocker and Roberts, 1971). Food, shelter, and clothing should also be added to the above list.

There is a definite correspondence between economic growth and the use of the environment. Moreover, there is no question that doing things the "natural" way cannot begin to feed, clothe, and house the population of the world. It is also likely, however, that the preferences of those in favor of a more natural environment are not accurately registered in the market or the political arena. It is one goal of government to give such preferences a proper weight.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

A second area of disagreement arises because of differences in the approach to achieving the objectives of each group. The ecologists and the economists might agree that the objective is to provide man with maximum opportunity for freedom to act, but the ecologists predict disaster if rivers are polluted, whereas the economists say that cleaning up rivers costs resources that could be used to feed the poor. There are always tradeoffs (Crocker and Roberts, 1971).

Figure 1 illustrates the kind of choices that are evident today. In this case, the choices lie between basic needs (consumer goods) and environmental quality. The line P_1P_2 represents various combinations of environmental quality and consumer goods that might be obtained from a given resource endowment. The section P_1A suggests that we might actually increase production in some cases while improving the environment from its worst possible state. Between A and P_2, however, there is a definite substitution that must occur between the two choices. To gain one requires giving up some of the other. As long as the people are dealing with a situation in which the basic alternatives (for example, food versus recreation) are being traded or transacted in the marketplace, the revealed preferences of the public may seem clear. The value placed on environmental quality may not always be so obvious, however. To the extent that the relative values placed on consumer goods and environmental quality can be compared, such a comparison allows people to determine the slope of the total utility/maximum revenue line (DD_1) as an indicator of the relative preference between the two alternatives. It can be shown, for example, that complete abatement of pollution from irrigation return flows would be very costly, and would probably include a significant reduction in national food production. The public might prefer to operate at point B, where a moderate supply of goods and yet a reasonably tolerable environment is possible. The environmentalists, however, might prefer to operate at point C, where there is a much less polluted environment, but a relatively low supply of goods. The producer might prefer to operate at point A, where production is maximized, but at a greater cost to the environment. A major problem in arriving at the socially desirable mix of commercial goods and environmental quality is that the preferences for these alternatives are indicated in different ways. Market prices serve to indicate the desire for consumer goods, but there is generally no such convenient method for indicating preferences for an improved environment.

The markets for trading privately owned goods help to solve a vast number of the problems of man with little conscious effort on the part of those involved. People own property rights to a large number of articles entering their lives. The exact procedure that must be followed in exchanging these property rights with one another depends somewhat on the kind of goods that we are trying to exchange. In the end, however, people are

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(4-76)

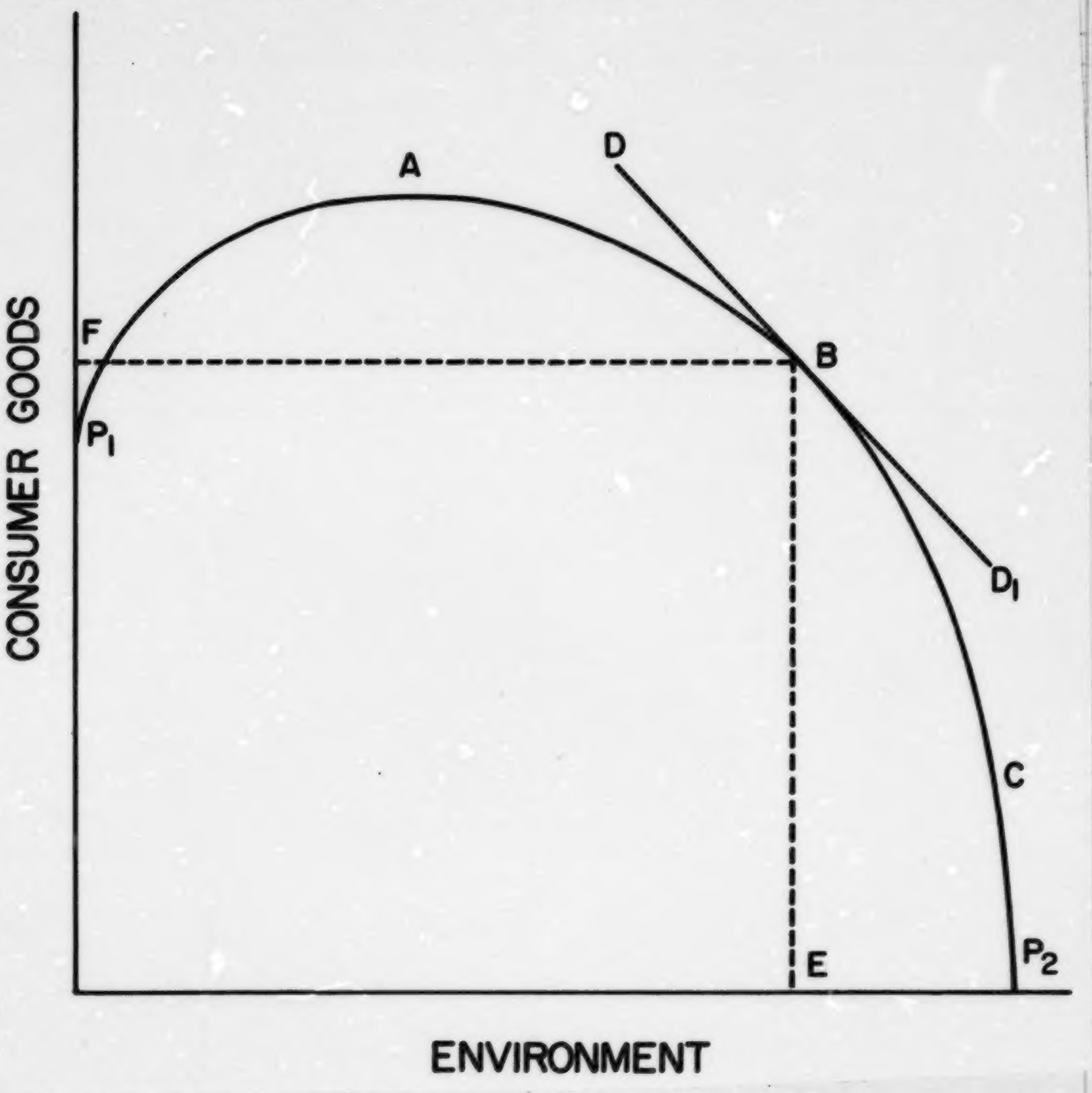

Figure 1. Potential alternatives in the choice between environmental quality and basic needs.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

generally able to find a buyer and a seller for every good at some price. If society is to protect the natural world, it must actively intercede on behalf on unutilized, underutilized, or endangered resources.

Agriculture is a smug but relatively nonresponsive industry when cast in this milieu. It is smug because its prime task is to turn nature into meat, vegetables, and fruit. It uses resources, but is generally proud of its record of "wise use" and its infrequent incursions into the domains of others. Odors from feedlots have caused problems, but the average farmer has seldom worried about pollution.

All this is changing. It is now known that many fertilizers and pesticides applied to agricultural land can slip into surface or underground watercourses and cause damage with respect to subsequent water uses. It is known that soil erosion can bring sediment damage or flooding on the lands of neighbors. Unlike industrial sources which can be clearly indentified, agriculture often produces diffuse and unidentifiable (nonpoint) sources of pollutants. Developing the means to deal with identifiable sources of pollution is difficult; dealing with the nonpoint variety is almost impossible.

While irrigation is important to U.S. agriculture, it can also cause environmental problems. Irrigation water acquires suspended solids and organisms, dissolved chemicals, and temperature changes. More importantly, it is reduced in volume by plant use and evaporation. These changes may affect its suitability for use by others.

High nitrate concentrations in irrigation return flows may contaminate drinking water supplies and cause human, as well as livestock, health problems. Because of this, the U.S. Public Health Service has established a maximum limit of 10 milligrams/liter (mg/l) nitrate-nitrogen for human drinking waters. Research has also shown that nitrogen levels over 0.3 mg/l, in combination with phosphate levels exceeding 0.01 mg/l, can cause vigorous algae growth. This may result in fish suffocation or other problems with water supplies. High sediment levels cause increased turbidity, channel obstruction, bridge damage, and irrigation equipment damage.

The markets are well equipped to guide resources into productive uses and to distribute economic rewards among members of the community as long as the public is dealing only with the class of goods or resources known as private property. There is, however, a large class of resources that are not susceptible to restrictive property rules. These are known as common property resources or, simply, as "community property."

If common property is present, everyone will use it, no one

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

will pay for it, and few will take the trouble to care for it. Environmental and ecological problems arise in such a setting. One individual, in striving to use common property to achieve his objectives, may cause detrimental effects to be imposed on others. Society has not developed adequate rules for using common property or for handling the diseconomies that arise from such use.

PROPERTY RIGHTS

Property rights are the rules that say who can do what with nearly all classes of natural resources. These rights are established by society and provide many clues about the means of solving problems of environmental degradation. Many of the rules by which our economy operates today were designed in a period when there was an abundance of common property and little concern about how one's use of a resource would affect the value of that resource to others. As time has passed, pressure on resources has increased and many earlier rules have become obsolete. This is especially true in cases where the distinction between common property and private property has become blurred.

Private Property

The private property rights conferred upon the owner of a tractor provide him with the privilege of exclusive use and the right to transfer the use of the tractor to anyone else whenever the transfer becomes advantageous. Generally, the value of such privately held items is determined in the marketplace. Society may impose rules that restrict the use of the item, but the individual who holds title to the item is the only one who can use the item within the bounds of the law. For example, a shotgun is private property and (usually) one person has exclusive rights to its use. Society has, however, imposed rules that restrict use of that gun in order to ensure the safety of those who are near the gun owner. Since safety has different meanings in different places, the rules for the use of the gun may be changed over time or space by the will of society.

Land ownership and use has many of the same characteristics. Society grants ownership and use rights of land to individuals, but may also impose restrictions on land use through zoning or building codes. Usually, some level of government must act to set and enforce standards of use. If all activities of all people were performed exclusively through the use of private property, the market would measure the positive value (utility) derived from the use of that good and would also reflect the damage to others caused by one person's use of the same good. Unfortunately, the market is not up to this task. A great deal of disutility (loss of value) is created by the use of private property items such as automobiles which emit exhaust fumes, or

EPA-287 (Cin.)
(4-76)

residues from fertilizers which are carried onto other properties or into public water resources by irrigation return flows.

Common Property

Common property rights appear at the opposite end of the spectrum from private property rights. They are not owned exclusively by one individual and are therefore nontransferable. Truly common rights are vested equally in each citizen, and allocation of common property resources among individuals becomes problematic. Many common property rights are allocated on a "first come, first served" basis. Two general types of services flow from common property rights. One set is subject to limited individual choice, such as the sailing, water skiing, or fishing services available from a publicly owned lake. Individuals may choose to utilize the wind for sailing or the water for fishing or skiing. If they are rational, users will participate in the activity only to the point where their marginal (additional) gain in satisfaction equals the marginal cost of participating in the activity. Water is an example of common property whose use may not be subject to individual choice. Downstream irrigators or municipalities may not be able to avoid the necessary use of water and the problems induced by upstream pollution.

There is no marketplace where users of common property resources can interact and negotiate to their mutual advantage. If one person's use of a common property resource serves to damage the incentive or reduce the profits of a second person, the second person has absorbed a cost that will be reflected in the value of his other resources. Pollution commonly yields this effect. Mutual benefits can occur when one farmer's drain system also lowers the water table on his neighbor's land.

Environmental degradation, or pollution, occurs when one user of a common property resource neglects to consider the fact that others may also wish to use the resource. Since there is no price for the user to pay, he uses as much as he pleases without regard for others. The market fails, and the planner is left with few rules concerning what can or should be done. No one can say unequivocally that too many or too few resources are being used or that too much or too little pollution is being produced.

Figure 2 is a basic representation of a market supply function and a market demand function for a traded good. The supply function SS_1 indicates those quantities of the good that would be provided at various price levels. Likewise, the demand function DD_1 shows the quantities of a particular good which would be taken (demanded) at the same price levels. The intersection of these two lines indicates the equilibrium price and quantity for the market. It is here that buyers and sellers

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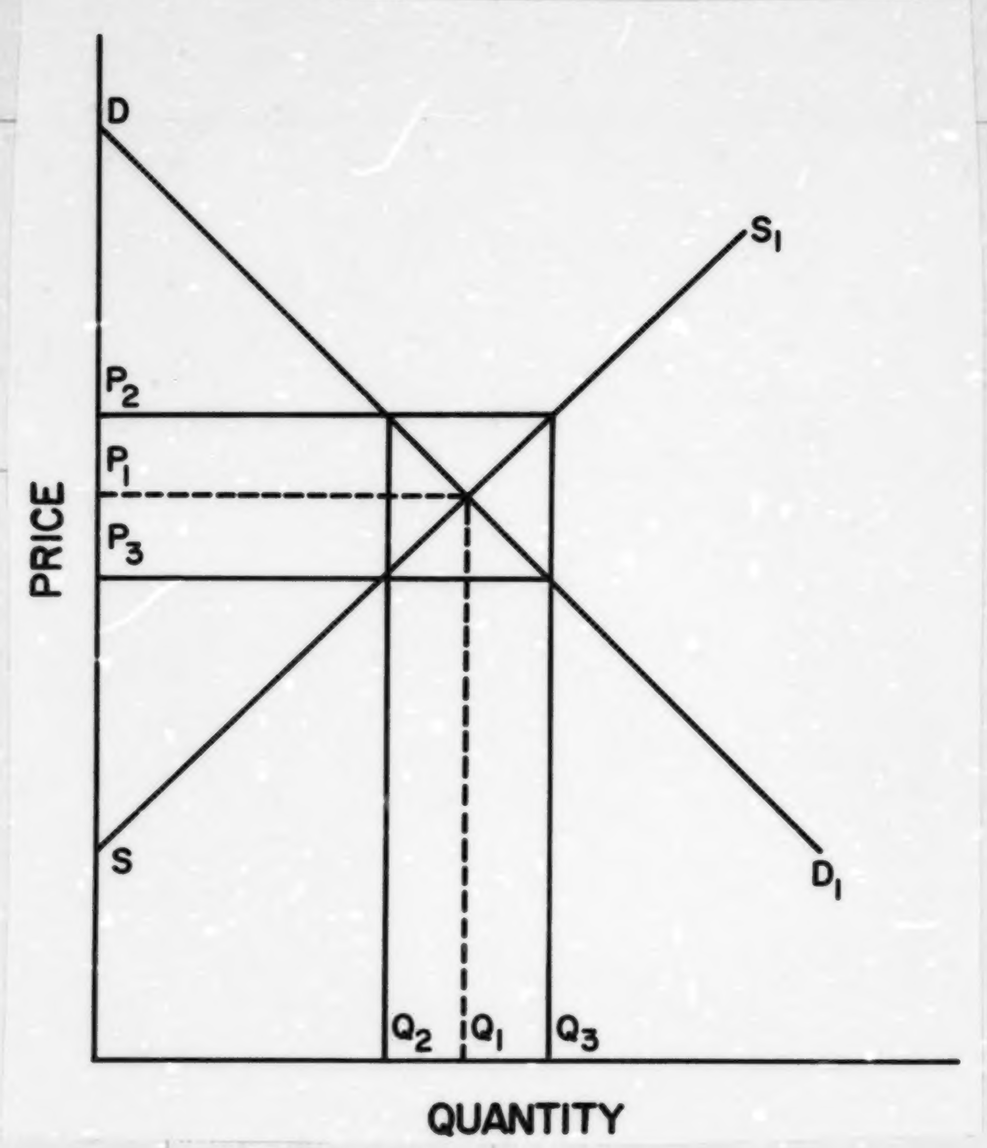

Figure 2. Market supply and demand functions for a trade good.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

exchange desired quantities of goods at desired price levels. If the system operates briefly at prices above this level, such as P_2, producers will supply too much, Q_3, and consumers buy too little, Q_2. There is a surplus equal to $Q_3 - Q_2$. This results in an eventual price reduction to P_3. The industry must reduce output in order to bring about a new equilibrium.

The supply function may be shifted to the right by an inducement of technology; for example, a new fertilizer. Conversely, it may be shifted to the left by the imposition of a tax on output, which increases cost. In agriculture, weather may cause the supply to vary from year to year. The demand function may likewise be shifted by changes in population, income, or tastes. Thus, the precise equilibrium of prices and quantities implied by Figure 2 is always sought but seldom achieved. Market prices, do, however, serve to guide the activities of all persons in the marketplace for allocating production processes and investments.

Problems arise because it is not possible to assign property rights to resources such as water and air. These public resources become the sinks for many of the discharges of unwanted production by-products in the economy. Some of the costs of producing a particular good are imposed on people outside the market regime of those actually producing the good. This phenomenon is illustrated in Figure 3. As in the preceding figure, the curve SS_1 indicates the supply of consumer goods being provided in a market economy. A quantity Q_1 can be provided at a price P_1. The demand curve for these consumer goods is indicated by curve DD_1. The production of goods, such as the food which comes from agriculture, can result in environmental degradation with costs falling upon others outside of agriculture. Hence, there is a social cost which the producers of food and pollution do not recognize in their decision making. If the costs of environmental degradation were assigned to the polluter or to the goods causing such pollution, it would raise the costs of those consumer goods to the levels of curve SS_1. After recognition of these additional costs, there would result a new equilibrium, providing fewer consumer goods at higher cost. In this case, the quantity produced would be reduced to Q_2 and the price raised to P_2.

Such "internalization" of pollution costs would solve many of our environmental problems, but it is difficult to achieve. As a substitute, society has decided through governmental action that pollution should be avoided or abated. The public is faced with the problem of trying to discover the most efficient means of achieving such environmental improvement.

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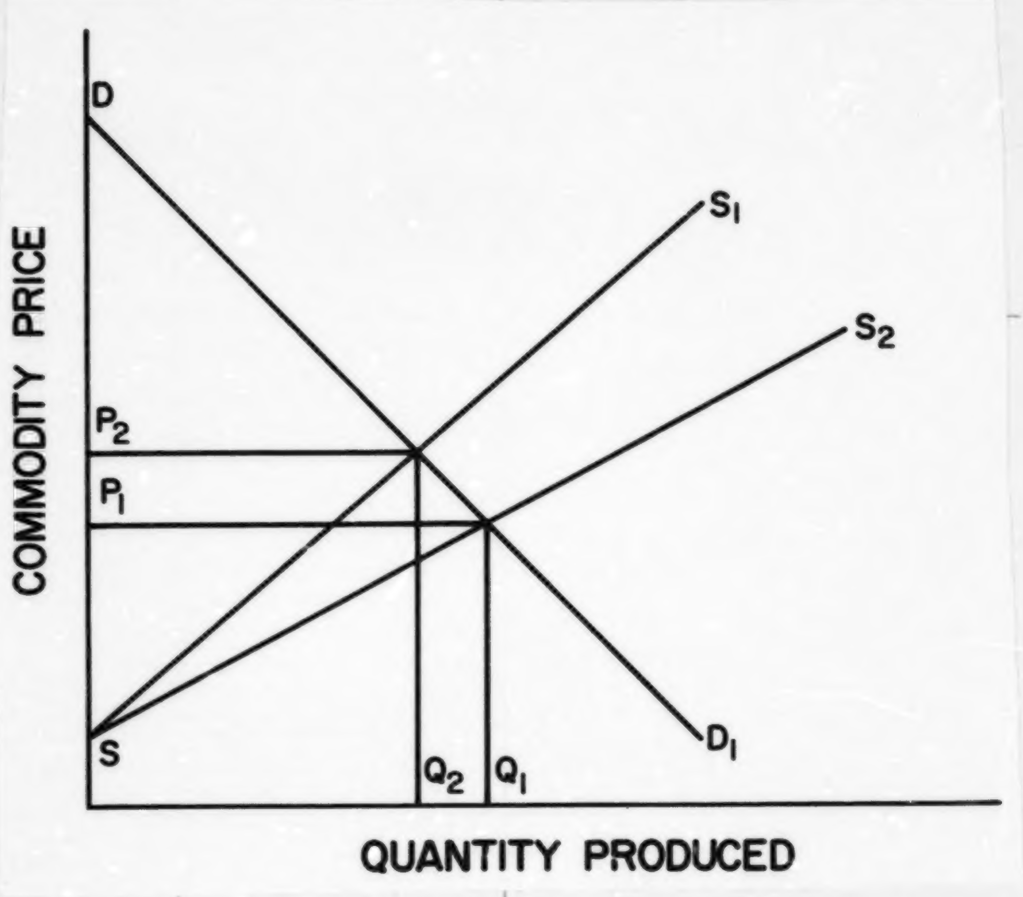

Figure 3. Adjustment in output that could result from recognition of environmental costs.

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EPA-287 (Cin.)
(4-76)

ECONOMIC CONCEPTS

Market prices generally serve to guide resources into their most beneficial uses. The prices of production factors and goods are assumed to represent the contribution of each to social welfare. If knowledge is perfect, even the level of pollution will not exceed the desires of society. Under such circumstances, the homemaker who buys beef in Seattle is assumed to be paying for the damage caused by odors near the meat packing plant or for damages due to stream pollution near the point of production. Obviously, these conditions do not hold in the real world. Pollution costs are not completely absorbed and land owners near the pollution source are not fully compensated.

Externalities

An economist describes imperfections in the production system as "externalities." A farmer will strive to maximize profits by combining land, water, fertilizer, labor, and sunshine to produce crops in an optimal and efficient way. In the process, he may create externalities such as air pollution (dust or odors) or water pollution (sediment or nutrients) which can harm or reduce the welfare of others. The farmer's instincts, however, tell him to maximize his own profits without regard for the welfare of his neighbors. He presumes that maximizing his own welfare will help to maximize the welfare of society. Since his neighbors harbor similar thoughts, each attempts to maximize profits and each disregards the damage which he may be imposing on others.

Opportunity Costs

Because many externalities are not easily measurable, it is necessary to devise schemes to determine their impacts. The economist relies heavily on the concept of opportunity cost for this purpose. Briefly defined, the opportunity cost of a resource is its value in its best alternative use. Water used for irrigation may yield a profit of $15 per acre-foot. If the same water were used to generate power, it might have a value of $20 per acre-foot. This $20 becomes the opportunity cost of water used for agricultural production.

This concept can be used to assess the impact of pollution that reduces the recreational value of a lake. The value of lost recreation is measured by the costs required to develop alternative means of recreation. Construction and maintenance of swimming pools, and travel to more distant lakes, may all be involved. Values may also accrue to the lost recreational opportunities that are irreplacable or unaffordable through conventional alternate means. The sum of these values becomes a part of the opportunity cost of the lost recreation, but they defy actual measurement in most cases.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The opportunity costs of resource use can be used to measure pollution costs and to help determine whether or not pollution abatement programs should be undertaken. Although the opportunity cost is the key to damage assessment, the distribution of damages among members of society is also useful in rendering opinions about allocating the costs of pollution abatement. In a sense, the size and distribution of opportunity costs become substitutes for the true economic values of pollution costs. They become a standard against which the benefits of pollution abatement can be judged.

The total costs of pollution can be high or low, but the real test comes in deciding who is responsible for them. If a person's cattle invade another person's cornfield, the distribution of costs is rather easily determined. The cattle owner gained and the cornfield owner lost until compensation has been paid. If return flows from irrigation in the Upper Colorado River drainage cause damage throughout the desert Southwest, however, the matter becomes more complex.

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Benefits of Abatement

The ideal criteria for setting pollution abatement standards would be to have a perfect knowledge of the costs of pollution damage or of the benefits of pollution abatement. Generally, the costs of pollution abatement are well known or easily discovered because they are determined in the marketplace. The measure of abatement cost used in this report is the decrease in net farm income for alternative management practices. The measurement of benefits from abatement continues to be elusive, however. Even factors that can be measured in economic terms, such as land values or production costs, are often difficult to quantify as a function of pollution abatement. Health, recreation, or aesthetic effects are nearly impossible to quantify in a manner that allows them to be compared with other, largely economic costs. What is the true worth of cleaner water?

Despite the problems of measuring pollution abatement benefits, people must strive to achieve some measurements. To the extent that people reach this goal, the public can be more confident that imposed environmental standards are optimally designed to meet social goals. In addition, the identification and measurement of benefits will simultaneously identify those who receive the benefits. The result is a more valid basis for distribution of abatement costs.

Income Distribution

In general, costs incurred because a person's cattle enter another person's cornfield can be measured as the change in income or welfare that the two individuals receive. One

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

person's income is reduced; another person's income is increased. In some cases, similarly, it is possible to add the changes in income of individuals in order to derive an estimate of total costs and benefits that stem from polluting activities or pollution abatement. In other cases, the costs may be so dispersed that no single entities are subject to significant change. In those cases, government must become involved in setting and enforcing standards, collecting taxes, redistributing wealth, and performing other activities that are beyond the scope or management of the individual.

If the problem of nonpoint source pollution is to be solved, the solution must come through group activity sponsored by the government. Assume for a moment that farmers in a river basin are polluting the river because their irrigation return flows carry fertilizer residuals. The government may seek to reduce pollution by imposing a tax on the fertilizer, the water, or both. Due to the increase in input prices, farmers will use less of each. In so doing, they will reduce the volume of pollutants reaching the river. The result is illustrated in Figure 3 by the change from supply curve SS_1 to curve SS_2. In Figure 1, it would be shown by moving from point B toward point C. Reducing pollution may also reduce the net incomes of farmers. The aggregate reduction of net income for all farmers in the basin becomes one measure of the costs of pollution abatement.

METHODS OF ABATEMENT

If common property did not exist or if people could control its use through markets in the same manner as for private property, most of the pollution problems would be automatically solved in the marketplace. Pollution would have a cost or value in each setting which reflected the problems created. Someone would have to pay the cost of polluting or someone would be willing to pay others not to pollute, depending upon the rules of the game. The result would be a level of pollution reflecting a mix of consumer goods and environmental conditions.

Common property resources are used as waste receptors at no cost to the polluter, however. Injured third parties then bear costs not included in the private cost calculations of the polluter. Social cost exceeds private cost, and there is not assurance that private resources are allocated most efficiently with respect to production or the environment. The result is generally that the economy produces and consumes too many market goods (good produced along with the waste product) relative to the desired environmental quality.

There are three broad classes of methods of solution to environmental quality problems. They are: (1) market solutions,

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EPA-287 (Cin.)
(4-76)

following the establishment of liability rules to serve as a starting point for negotiations; (2) systems of per-unit taxes, charges, fines, or subsidies designed to alter pollution levels by influencing production methods; and (3) systems of standards, enforced by the threat of fines or jail sentences.

Market Solutions

It is necessary to clearly define property rights and laws of liability before market negotiations can take place concerning externality problems. In general, there are two extremes of liability (zero liability and full liability) in terms of pollution problems. There is also an infinite number of intermediate possibilities. Full liability charges the polluter with the full responsibility and cost for abating pollution or compensating those affected by pollution. Under zero liability, the polluter has no responsibility for unilaterally reducing pollution or for compensating those who are being damaged by the pollution.

Under partial liability (a third or more normal case), the acting party may pollute up to a certain point without compensating the affected party, but after that point compensation must be paid. Partial liability rules often prevent the affected or affecting parties from extorting unreasonable compensation from the liable party by claiming excessively large damages or abatement costs. Partial liability rules can be devised to recognize the ability of the environment to assimilate a certain amount of waste without significant external effects.

In the following discussion, the term "transaction costs" refers to the costs of making and enforcing decisions regarding pollution control. These are the costs that would be faced by involved parties under any liability rule in getting together and arriving at solutions to pollution problems. In the presence of transaction costs, market solutions may differ under alternative liability rules. That is, the costs of arriving at a solution can actually affect the outcome of the possible solution. With the full liability rule in effect, for example, very large transaction costs could result in the polluter being unable to compensate the receptors, so complete abatement would result. A dairy or feedlot might be polluting a river and faced with the full responsibility for abating all such pollution or paying all affected citizens an amount sufficient to allow some level of pollution to continue. The firm would most likely find it too costly to seek all affected parties and to arrive at an acceptable level of payment. It would be cheaper to cease production instead.

There are other problems with bilateral bargaining, even in a voluntary setting without transaction costs. One is the problem of threats. If the railroad is not held responsible for

EPA-287 (Cin.)
(4-76)

sparks and the consequent burning of farmer's crops (zero liability), the railroad could very well threaten to run more trains unless the farmer overcompensated the railroad's costs of running fewer trains. A form of blackmail or extortion results. A second problem is that the bargaining behavior of people is rarely marginal (i.e., concerned only with the next additional unit of bargained material). The fence builder and the fence hater do not bargain over each inch of fence height. Thus, there is no guarantee that the resulting height of fence is optimal. The only way that optimality is likely to result is if there are many involved parties to repeat the bargaining process numerous times. Then there would probably be large transaction costs, however, and an optimal solution might still not be generated.

Under a zero liability rule, the acting party which receives the payment will have more capital with which to work, and may produce even more (with the subsequent ability to pollute more as well). Under a full liability rule, the acting party will have its working capital reduced because of the need to pay compensation or invest in pollution control devices. Hence, this party will produce and pollute less. The amounts of production and pollution can be influenced markedly by the imposed liability rule.

Transaction costs are likely to be larger when negotiations must be initiated by large and diffuse groups of individuals rather than by a few individuals having common interests. Thus, it follows that the full liability rule is more likely to have smaller transaction costs than the zero liability rule, and more of a chance for abatement. The full liability rule has generally been followed in solving point source pollution problems.

There is normally a large number of affected parties in pollution problems. With zero liability, the marginal benefits received from abatement negotiations by any single individual would probably be less than the costs of negotiation and transaction. Since any receptor can benefit from another's negotiations with the emitter, there is likely to be a hold-off among receptors in anticipation that other receptors will initiate the negotiations. The outcome is likely to be little abatement. Bargaining can be very cumbersome and expensive when the group of receptors is large and diffuse. The problem is compounded when the pollution merely reduces utility or aesthetic value of the resource, but does not directly affect economic income of involved parties.

Full liability is also not without problems. Emitters must find receptors with which to negotiate. This can be very expensive. Blackmailing, by threatening to become a receptor and yet avoiding negotiations in hopes of higher payments, also constitutes a serious problem. When negotiation and transaction costs

EPA-287 (Cin.)
(4-76)

are added to compensation costs, other alternative solutions (such as pollution control devices) may be less costly. The resulting resource allocation may not be most efficient, as too much abatement may result if abatement costs exceed abatement benefits. Efficient solutions require a setting in which no parties can demand excessive compensation for costs.

With the zero liability rule, little incentive exists for an emitter to develop or use pollution control devices. Farmers polluting through irrigation return flows generally fall in this category. Farmers may adopt pollution reduction technologies, but only if compensated for additional costs in some manner. The alternative is to shift the liability onto the farmer through threats of fines or jail sentences. In abating pollution from irrigation return flows, it is generally believed that the zero liability rule will be approached, with farmers being almost fully compensated for costs incurred by pollution abatement activities.

Full liability rules carry an incentive to adopt environmentally sensitive technologies. Such rules also promote the location of polluting businesses in areas where external costs to society are small. An additional argument for the full liability rule can be made on the grounds of equity. If polluters are more prosperous than affected parties, the full liability rule helps to "redistribute the wealth" and once again is more equitable than a zero liability rule.

Market bargaining will be an efficient means of solving pollution problems only under certain assumptions. In other cases, nonmarket policies must be implemented instead. Such policies include effluent standards, effluent taxes, subsidies, output taxes, input taxes, and input limits. Though generally resembling full liability policies, these solutions are controlled by government or regulatory groups, rather than by market negotiations.

Effluent Standards

Effluent standards or emission rights are effectively a means of assigning liability limits to polluters. An effluent standard, for example, could state the amount of sediment, nitrates, or irrigation return flow allowed to leave the farm. Such standards result in the polluter being forced, through government decree, to abate some or all of his pollution. There may or may not be assistance for the polluter in the form of subsidies for meeting the costs of pollution abatement. Some state-level planning in the Pacific Northwest is taking this approach to the problems associated with irrigation return flows.

A policy of issuing rights to farmers allowing a specific amount of pollution is conceivable but unlikely. The total of

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

the emission rights issued would be determined by the environmental standard to be achieved. It would be desirable to allow trading (buying and selling) of the rights among farms within a river basin or watershed in order to allow all farms to equate their marginal costs of abatement. Farms relying on old irrigation systems or located on soils which are difficult to control could buy rights from others in order to increase their level of emissions and thus stay in business. Those farms selling part of their emission rights would have to meet a higher abatement standard.

An effluent standard is the same as a fixed resource to the farm. It can be used up to its limits, but not exceeded. The value placed on the standard shows the farm's value to the environment for waste disposal services, just as the price for land shows its value for crop production. Emissions by effluent standards may result in unfair allocation of resources, unless trading is allowed or the initial level of allocation is based on ability to meet the standard. In addition, firms benefit from overstating their abatement costs, resulting in levels of emissions which are higher than necessary. An additional disadvantage of this approach is that it does a relatively poor job of inducing pollution abatement technology.

The use of an emission rights (effluent standard) policy is probably not well adapted to the nonpoint source pollution problems of agriculture, because it requires that the level of pollution coming from each farm be identifiable and measurable. Otherwise, there is no practical means of enforcing the policy. The implications of this type of policy could be useful in determining optimal abatement policies for a river basin, however. To meet a given environmental goal in a river basin, it might be desirable to force some farms to meet higher standards than others, while having all farms share in the associated costs.

Effluent Taxes

Rather than issue permits or standards for pollution, it is possible to impose a tax on emissions. This tax is to be paid by the polluter. Firms will react by abating pollution as long as the abatement costs are less than the tax, and beyond that point they will pollute and pay the tax on emissions. Tax rates can then be adjusted to achieve the desired level of pollution abatement.

If sufficient information exists to measure the benefits of abatement, it is possible to set the effluent taxes at exactly the proper level, e.g., so that benefits of abatement equal abatement costs. A more likely situation however, is to have little information about the actual economic value of abatement benefits. In this case, a desirable environmental quality

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

standard is selected and then the effluent tax is adjusted to meet the standard at minimum cost. This approach presumes a full or partial liability rule to be in effect, with appropriate enforcement by government interference.

There are similarities and differences between effluent standards and effluent taxes. If the emissions of a firm are a constant proportion of its output (e.g., tons of potatoes), the firm reacts to an effluent standard or tax by reducing pollution until the standard is met or until profit is maximized. If the emissions of the farm are a function of input (e.g., water or fertilizer) instead, the firm alters its combination of inputs in response to the effluent tax or standard. For any given effluent standard, there is a tax that will result in the same degree of reaction by the firm. That tax rate is equal to the marginal abatement cost at the given standard of pollution.

There are differences in the effects of these two approaches (the effluent tax and the effluent standard) as well. To achieve a given level of abatement, a uniform effluent standard may have some undesirable effects in comparison to a uniform effluent tax. A uniform effluent standard will cause each firm to meet the same level of emissions regardless of the ability of the firm to do so. Some firms may, therefore, be forced out of business. An effluent tax, on the other hand, can allow those firms unable to meet a specific standard to at least remain in operation by paying the tax and continuing to pollute. The aggregate income loss to the industry should be about the same in each case.

Unless the initially imposed tax or effluent standard is at exactly the right level, firms will incorrectly respond by making suboptimal investment decisions on the basis of improper tax rates. There is the additional problem of setting up a government tax program without knowing the proper tax rate or the amount to be collected. Standards also cannot be indiscriminately changed or adjusted without imposing serious and unnecessary hardships on most industries.

The emission standard and the effluent tax require that the effluent from a firm be readily identified and measured. This requirement is virtually impossible to meet for nonpoint source pollution, including irrigation return flows. The standard may still have some virtue, however, if applied to an identifiable outflow from an entire irrigation district. The management of the irrigation district could then choose its own approach to meeting that standard.

Subsidies

Subsidies to reduce emissions are similar to taxes in several respects. Using subsidies, the payment is from the

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

public to the polluting firm. A level of subsidy can be devised to achieve the same level of abatement as with a tax. Firms will theoretically adjust production or use of inputs that are contributing to pollution until the level of foregone income exactly equals the level of the subsidy. This approach is obviously subject to cheating if the polluter overstates his abatement costs or accepts the subsidy and then continues to pollute. It requires careful identification of polluters and continual monitoring of their abatement programs. It is one approach which is commonly advocated for influencing farmers to adopt abatement control practices, however.

In the long run, effluent taxes and subsidies may have opposite effects on an industry. Taxes will reduce the amount of effluent within an industry. Subsidies will reduce the amount of effluent discharge per firm, but may actually increase the amount of effluent from the industry, due to the entrance of new firms. This is because profits are not reduced by a subsidy program. Irrigation may even expand into areas with large environmental problems, because it is known that the public will ultimately pay the costs of solving such problems.

Output Taxes

It is also possible to impose a tax on the product or good whose production is causing the pollution. Again, a tax level is devised that will result in the desired level of pollution abatement. A tax on the product may be partially passed on to consumers in the form of a price increase if the entire industry faces the same output tax. Whenever the tax is imposed on only a small portion of the industry, however, that portion of the industry will probably have to absorb the additional cost or switch to another product, since it will be unable to sell its product at a price above that set by the rest of the industry.

An output tax does not effectively alter the prices of inputs used in production. Thus, the combination of inputs remains unaffected. For any level of abatement, an effluent (pollutant) tax will generally be less costly than an output tax except when the output and pollutant are produced by only one input. This is a rare circumstance.

An output tax generally has only limited use in agriculture, since most pollution is a function of only a few inputs (such as water, fertilizer, or chemicals), and yet many total inputs are needed to create the output. Effluents would be reduced only in relation to output reduction, and input substitution would not be encouraged (e.g., increasing management or labor to reduce the amount of water and fertilizer used). A policy encouraging resource substitution would be more efficient in improving agricultural water quality. In other words, a policy to reduce pollution of irrigation return flows would be

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

more efficient if focused on such inputs as water and nitrogen than if guided by a tax on crop production.

Input Taxes and Limits

Taxing or rationing of those inputs which are responsible for pollution, rather than taxing the effluent directly, is a more likely policy for agricultural pollution abatement. The need for identifying and measuring levels of emission by individual firms is eliminated. This policy alternative is practical only if the effluent results from a limited number of inputs, however. If there is only one input contributing to an effluent, taxing it or rationing its use can be as efficient as an effluent standard. If two inputs contribute to effluents (e.g., water and fertilizer), then taxing or limiting only one input will be less efficient than an effluent tax or standard. Only by taxing or limiting both inputs in direct proportion to their contribution to effluents will maximum efficiency be reached. If taxing or limiting input resources brings input prices in line with their true social costs, then pollution will be reduced to the socially desirable environmental standard. Through such means, input use could be adjusted to achieve the desired level of water quality.

Uniform input limits or taxes applied across regions will not be equitable if regional pollution problems and production methods are not uniform. Unless a variable input limit or tax system is used, trading of input use rights should be allowed to equalize costs among regions or among farms within each region. In an irrigated river basin, the agency in charge should estimate the total amount of water to be used within the basin and then appropriately reduce the amount of water to each farmer.

DETERMINING THE "CORRECT AMOUNT" OF POLLUTION CONTROL

The proper means of controlling pollution--especially nonpoint source pollution--should be chosen with some care. The choice should be tempered by careful reflection on the distribution of costs and benefits accruing to each of the alternative plans. The effectiveness of a pollution control program may appear vastly different, depending upon one's vantage point. A tax penalizes the polluter and provides revenue. A subsidy asks society to buy out the offender. A law reduces the income of the offender as well as the amount of product available to society. It may not be clear which means of control is most desirable in a given nonpoint source case.

Most citizens will agree that the United States is too heavily polluted. Most would similarly agree that something should be done about the problem. There is little agreement, however, on how much should be done. One thing is certain:

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EPA-287 (Cin.)
(4-76)

each of the several methods of control will, if left to itself, yield a different amount of control. Interested and affected parties choose different criteria, depending on whether they are on the side of the polluter or on the side of those who are injured by the pollution. The decision is thus arbitrary. At this point, no particular view can be judged to be either right or wrong. There still remains, however, a choice as to the level of abatement to be achieved. Some criteria for making this choice are discussed below.

Zero Pollution

Zero pollution is not a means, but an end. Such an end is an extreme position advocated by some zealous individuals and environmental groups. It is questionable whether zero pollution can even be met in nature, let alone under the conditions imposed by an industrial society. All human activity alters the environment in some way. Rules insisting on zero pollution are not generally taken seriously, because most people realize that there is little room for economic activity in such cases.

The Economic Optimum

Common sense indicates that there can be too little as well as too much pollution. If these two extremes can be identified, there must also be some amount that is "just right" (Figure 1). In a perfect world where all effects and all costs are measurable, the optimum would be defined by extending pollution control activities to the point where added expenditures for control are just offset by added benefits. This is a familiar rule in all of economics and it has a common sense interpretation: keep doing something as long as it pays.

One can imagine a large industrial plant dumping waste into a river. Water might be subsequently taken from the river to be used for a municipal water supply. Pollution abatement procedures could be initiated to force the plant to clean up its own mess. The plant would pay and the downstream city would benefit. As long as increased costs of abatement were covered by dollar savings to the city (in terms of water purification or water supply costs), society could recommend that more and more pollution abatement capacity be added to the plant. Marginal benefits would exceed marginal costs.

This method of approach, however, breaks down in nonpoint source pollution cases. Although an optimum may exist, the physical and economic data appropriate to that optimum are largely unknown. It is not known whether one of the hundreds of polluting farmers could solve the entire problem if he were to discontinue all activities contributing to the problem. Nor is it known whether a 10 percent reduction in all polluting activities would necessarily reduce pollution by 10 percent. The

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EPA-287 (Cin.)
(4-76)

economic optimum cannot be precisely determined. All that is known is that it is generally between present and zero levels. Policy makers can recommend that all farmers use best possible management practices in order to achieve an acceptable level of pollution control, or they can set arbitrary standards and attempt to enforce these by laws, taxes, subsidies, or combinations of the three.

Best Management Practices

Those working closely with agriculture often claim that the only realistic pollution standards for this industry are those that can be met by applying best management practices (BMPs) to each farming enterprise. This position is not without its problems. It says nothing about the relationship between economic activity and pollution. Recommending BMPs always begs a question: best with respect to what? There are BMPs that relate to water, to land, to the farmer's labor, or to the farmer's credit rating. These are not necessarily the same. Hence, each set of best practices may yield a different pollution loading for a stream or for the atmosphere.

It is likely, in most cases, that the application of BMPs would significantly improve water quality or environmental conditions affected by agriculture. There is no guarantee, however, that such practices would produce an optimal amount of pollution control. There also remains the problem of how to get farmers to adopt a specific set of management practices, particularly if those practices increase production costs or reduce income. Subsidies are apparently the chosen vehicle for implementing such practices.

Arbitrary Standards

Although the word "arbitrary" sounds unscientific and nontechnical, it may be the only way to approach certain types of pollution abatement. The term "arbitrary" must be tempered by reason, so arbitrary rules are not to be confused with ridiculous rules. Agencies charged with the responsibility for improving our environment are frequently left with few rational criteria for setting standards. They must strike a balance between affected parties demanding complete abatement and polluters who provide convincing arguments for continuing current activities. The result is often a bounded set of standards that may be designed to prevent further degradation of a local environment or designed to meet certain health-related criteria of water or air quality. The final set of standards will probably depend upon some combination of the attitude of the enforcement agency, the relative bargaining power of affected parties, the apparent seriousness of the pollution problem, and the knowledge and tools available for alleviating the problem. This approach requires each affected party to study carefully its own problems.

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Local citizen input is also likely to make the eventual solution more palatable.

Even using arbitrary standards for pollution abatement, there still remains the problem of how best to achieve the chosen standard. The choice of an abatement enforcement tool will ultimately determine the costs of abatement and the distribution of those costs among the members of society.

SUMMARY

Agriculture in the United States is a highly intensive industry that uses complex sets of inputs to produce huge volumes of foodstuffs. The industry has been held up as a picture of efficiency and as a model for other parts of the world. Only recently have environmentalists begun to point to agriculture and indicate that some environmental problems may arise in that sector of the economy. Nonpoint source pollution from irrigated agriculture could be ended by stopping agricultural production or by reducing output to pitifully small levels. It could also be stopped by generating a new class of inputs that leave fewer pollutants or that are less amenable to transport into other areas or into common property resources. In any event, the structure of the industry would change in response to the change in rules about input use. The new rules would also change the output mix of agriculture, the size and distribution of income within the industry, and the relationship between agriculture and local or national economies.

There is a certain amount of arbitrariness associated with pollution control policy. Regardless of this characteristic, such policies will always divide society into gainers and losers. A tax will impose costs on one set of people; a subsidy will cause others to bear the cost. An arbitrary allowable level of pollution will cause still another distribution of gains and losses.

Pollution, degradation, and despoilation are problems stemming from technical activities. It is reasonable that most solutions to such problems be sought by investigating technical relationships, so the engineer, the limnologist or ecologist, and the forester may all play important roles in assisting with problem solution. A major consequence of despoiled environments, however, is a rearrangement of social relationships among individuals and groups. The social scientists and economists must provide inputs to this aspect of the problem.

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SECTION 6

SEDIMENT AND NUTRIENT LOSS ESTIMATES (BACKGROUND)

The discussion to this point has concentrated on appropriate characterization data for irrigated portions of the Pacific Northwest, and on the economic background for pollution control decisions. Because of the diversity of crops, slopes, irrigation systems, and soils which are found throughout the region, no attempt will be made to provide generalized sediment and nutrient loss estimates. Instead, the types of information available from the literature with respect to such losses will be briefly summarized, and a methodology will be presented for estimating losses based upon current understanding. This methodology will then be applied to selected areas of the Pacific Northwest. Planners or researchers dealing with other areas from the region would apply similar methodology to their own conditions, and to projected changes in such conditions.

DETERMINATION OF IRRIGATION REQUIREMENTS (BACKGROUND)

Irrigation Efficiency

A useful parameter for estimating runoff and deep percolation losses (with which sediment and nitrogen losses tend to be associated, respectively) is the on-farm irrigation efficiency. This term is defined as the fraction of water applied to an irrigated field that is stored in the crop root zone. The remainder of the water is lost as evaporation, runoff, or deep percolation.

The crop root zone can be defined as that depth of soil that is penetrated by crop roots. Depending upon the type of study, it may or may not include a limited depth of soil below the actual depth of root penetration from which water is removed by upward flow between irrigations or storm events. This distinction can usually be ignored in well-irrigated settings, however. Typical rooting depths for various crops common to the Pacific Northwest are shown in Table 6. The tabulated values assume that no obstructions to root growth are present, such as hard pans, chemically cemented layers, or dry soil.

On a project-wide basis, appreciable evaporation can occur

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(4-76)

TABLE 6. TYPICAL ROOTING DEPTHS FOR MAJOR CROPS OF THE PACIFIC NORTHWEST

Crop	Depth (ft) a/
Alfalfa	4
Small grains	3
Pasture	3
Peas	2
Field corn	3.5
Sugarbeets	3.5
Dry beans	2
Potatoes	2

Source: Soil Conservation Service, 1973.

a/ 1 foot = 30.48 cm.

from open conveyance structures, such as canals. The problem of on-farm evaporation is normally considered negligible for furrow-irrigated settings, however, though it can account for as much as 10 percent to 15 percent of the total water delivered by most sprinkler systems. The higher values for sprinkler systems arise from the positioning of sprinkler nozzles above ground level, and the fact that they provide water in fine droplets which maximize subsequent evaporation. A value of 10 percent evaporation from sprinkler-irrigated fields will be assumed for the purposes of this study.

In general, surface runoff is only considered of consequence for furrow irrigation. Sprinkler irrigation systems can also result in localized runoff and erosion problems when heavy application occurs near the periphery of center-pivot sprinkler systems on moderate to fine-textured soils. This runoff often accumulates in the same field or in nearby depressions. Such localized runoff has been ignored for the purposes of this study.

Deep percolation can be defined as that quality of water which moves vertically through the soil below the crop root zone. Though subsequent upward movement is common under non-irrigated conditions, deep percolation is normally unavailable for crop use in well-irrigated settings. The same would not be

EPA-287 (Cin.)
(4-76)

true for settings subjected to deficit irrigation. In terms of project-wide irrigation efficiencies, seepage from conveyance structures like canals should also be included in the deep percolation term. In some studies, it may also be necessary to include seepage from farm ditches in on-farm efficiency calculations.

Coarse-textured soils allow more rapid infiltration and percolation of water than do fine-textured (high-clay) soils. For this reason, coarse-textured soils have a larger potential for deep percolation. Fine-textured soils, on the other hand, have a larger potential for surface runoff and erosion. Soils that are extremely coarse-textured may even result in such large percolation losses that furrow irrigation is not practical, so sprinkler irrigation must be used.

Water Holding Capacity

Fine-textured soils also hold more water than do coarse-textured soils. Table 7 provides typical water holding capacities for major soil texture classes in the Pacific Northwest. These water holding capacities are derived from soil "field capacity" values, with field capacity being defined as the amount of water remaining in a soil 24 to 48 hours after a heavy irrigation, under conditions of free drainage.

Depletable Soil Moisture

Depletable soil moisture can be defined as the quantity of moisture which may be withdrawn from the root zone without resultant crop moisture stress. At its maximum, it is the water held between "field capacity" and the "permanent wilting point."

TABLE 7. TYPICAL WATER HOLDING CAPACITIES FOR MAJOR SOIL TYPES OF THE PACIFIC NORTHWEST

Soil texture	Water holding capacity (in/ft) a/
Sand	1.08 b/
Sandy loam	2.04 b/
Silt loam and loam	3.12 b/
Clay loam	4.50 c/

a/ 1 inch/foot = 0.0833 cm/cm
b/ Source: Soil Conservation Service, 1973.
c/ Estimated by comparison with other values in the table.

EPA-287 (Cin.)
(4-76)

At the permanent wilting point, however, water moves so slowly through the soil that it is virtually unavailable to the crop. For sustained economic crop production under irrigated conditions, only one-half to two-thirds of this total moisture range should be regarded as truly depletable. Unacceptable moisture stress and yield reduction would result if the permanent wilting point were approached prior to each irrigation.

For a given crop, coarse-textured soils have a smaller depletable moisture range than do fine-textured soils. Crops with deeper root systems also have larger depletable moisture values, and crops vary in their sensitivity to moisture stress. For example, although most crops are assumed able to repeatedly remove up to approximately 50 percent of the depletable soil moisture without resultant yield losses, potatoes are often assumed able to remove no more than 33 percent of the depletable soil moisture without a loss in yield or tuber quality.

Table 8 presents depletable soils moisture values for major crops and soil types of the Magic Valley area of Idaho, and the Umatilla area of Oregon. The values (D) were computed using the relationship:

$$D = k(r)(w)$$

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where k = a constant equal to 0.5 for all crops except potatoes, where it is equal to 0.33 (J.R. Busch, Department of Agricultural Engineering, University of Idaho, personal communication, 1978); r = crop rooting depth in feet (Table 6); and w = soil water holding capacity in inches per foot (Table 7).

Frequency and Number of Irrigations

Irrigation frequency and number of irrigations per season are determined by the time required for depletable moisture to be extracted from the crop root zone. Irrigating too frequently results in excessive runoff and deep percolation losses. Not irrigating frequently enough results in crop moisture stress and subsequent yield reduction. Under ideal conditions, a crop grown in a coarse-textured soil would be irrigated more frequently than the same crop grown in a fine-textured soil. For a given soil texture, a crop with a shallow root system would be irrigated more frequently than a deep rooted crop, other factors being constant.

Table 9 shows the estimated numbers of irrigations per season for major crops and soil types of two Pacific Northwest irrigated areas. Omissions from the table indicate that the given crop is not a major one for that particular area. The relationship for determining numbers of irrigations (F) is:

$$F = Q_c/D$$

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TABLE 8. ESTIMATED DEPLETABLE SOIL MOISTURE VALUES FOR MAJOR CROPS AND SOIL TYPES IN THE MAGIC VALLEY AREA OF IDAHO AND THE UMATILLA AREA OF OREGON

	Soil Type		
Crop	silt loam or loam	sandy loam	sand
	-------------	(inches) a/	-------------
Alfalfa	6.24	4.08	2.16
Small grains	4.68	3.06	1.62
Pasture	4.68	3.06	1.62
Peas	3.12	2.04	1.08
Field corn	5.46	3.57	1.89
Sugarbeets	5.46	3.57	1.89
Dry beans	3.12	2.04	1.08
Potatoes	2.08	1.36	0.72

Note: Based on an assumption that 50 percent of soil water-holding capacity is readily available for all crops except potatoes, for which the proportion is only 33 percent.

a/ 1 inch = 2.54 cm.

where Q_c = seasonal net irrigation requirement of the crop (a concept to be discussed in greater detail below) in inches or cm; and D = depletable soil moisture in the same units (e.g., Table 8).

In practice, factors such as water needs by other crops on the same farm or in the same area, water availability, needs of water for wind erosion control or for promoting selective crop or weed emergence, individual preference for light irrigations versus heavy irrigations, and availability of irrigation labor are also important in determining irrigation frequency. Although scientific irrigation scheduling is becoming increasingly more common throughout the Pacific Northwest, there remain considerable differences between growers as to when a given crop is judged ready to irrigation. At present, irrigation frequency is a highly subjective determination throughout the region.

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EPA-287 (Cin.)
(4-76)

TABLE 9. ESTIMATED NUMBERS OF IRRIGATIONS PER SEASON FOR MAJOR CROPS AND SOIL TYPES IN THE MAGIC VALLEY AREA OF IDAHO AND THE UMATILLA AREA OF OREGON

	Magic Valley		Umatilla Area
Crop	silt loam and loam	sandy loam	sand
Alfalfa	6	9	19
Spring grain	5	7	--
Winter grain	5	8	15
Pasture	5	8	--
Peas	5	8	--
Field corn	4	6	15
Sugarbeets	5	8	--
Dry beans	6	10	19
Early potatoes	--	--	39
Late potatoes	13	19	51

Coefficient of Uniformity

Any system of irrigation, whether it be furrow or sprinkler, results in nonuniform application of water over the surface of the field. In furrow irrigation, for example, considerably more deep percolation occurs immediately beneath irrigation furrows than beneath adjacent crop rows, particularly on coarse-textured soils. In addition, the top portions of furrow-irrigated fields generally receive more water than do the bottom portions, so deep percolation losses are greater for the former. Under sprinkler irrigation, overlapping sprinkler patterns result in double applications to some parts of the field, while other portions receive less than a full application. Variations in water application uniformity are often described by the "coefficient of uniformity," with a value of 100 percent denoting completely uniform water application. Values for existing sprinkler systems are more commonly in the range 60 to 80 percent, and tend to be even lower for most furrow systems. Improving the uniformity of water application reduces runoff and deep percolation losses. This, in turn, results in increased irrigation efficiency.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Adequacy of Irrigation

The concept of "adequacy of irrigation" is not used extensively at present for irrigation management in the Pacific Northwest. With current emphasis on variability of water application and nutrient leaching, however, it is a concept which may be used with increasing frequency in the years ahead. The term can be defined as the percentage of the root zone throughout a field which is restored to field capacity during each irrigation. Since present-day irrigation systems do not apply water uniformly across the field, obtaining an adequacy level of 100 percent is not possible without incurring substantial percolation losses. In order to meet crop water needs, most fields are irrigated to an adequacy level of 75 to 87.5 percent. The higher level is commonly sought by U.S. Bureau of Reclamation design criteria. As will be shown in a subsequent section, however, such a level is rarely met in fields having normal variations in water application. The value of the crop, the importance of uniform field appearance to the grower, and the availability of water and nutrients all interact to determine the appropriate adequacy level for a given setting.

Length of Set

The time period that water is continuously applied to the field with furrow or sprinkler (not including center-pivot) irrigation, or the length of time required for a center-pivot revolution, can be defined as the length of set. It has less meaning for center-pivot systems than for systems where a given portion of the field receives water for a clearly-defined period of time. Other factors being constant, the adequacy of irrigation should increase with length of set. Coarse-textured soils or shallow-rooted crops should require a shorter length of set (but more frequent irrigations) than should fine-textured soils or deep-rooted crops.

In practice, however, the length of set is more commonly determined by convenience rather than by exact field needs. The most common length of set is 24 hours, so that irrigation lines, or siphon tubes, can be changed at a specified time each day. A less common length of set, for fine-textured soils, deep-rooted crops, or sprinkler lines applying water at low rates, is 48 hours. For center-pivot systems, care is usually taken to ensure that a single revolution is completed in other than a 12-, 24-, 36- or 48-hour period. This is done to prevent recurring application of water to a given part of the field at the same time of day, for less water remains in the root zone following mid-day irrigation than following irrigation at night or during early-morning or late-afternoon periods.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Stream Size and Length of Run

Stream size normally refers to the size of irrigation water stream delivered to the head of irrigation furrows. Because of infiltration along the furrow, it differs markedly from the size of stream flowing from the tail-end of that same furrow. Stream size is an important factor affecting furrow advance rate, or the velocity at which the initial water stream moves down a previously dry furrow. A larger stream size results in a faster furrow advance rate at a given site, other factors remaining constant.

Other factors also affect the furrow advance rate. Fields with steeper slopes, finer-textured soils, and relatively smooth furrow surfaces all result in greater furrow advance rates. Conversely, for example, recently tilled furrows result in a slower furrow advance rate. A shorter period of water movement to the end of the field results in less deep percolation near the head of the field, since this portion is then being irrigated for a shorter period in relation to the total time over which the entire field is being irrigated. Hence, the uniformity of application is increased. A faster furrow advance rate may also result in greater runoff if stream flow is not reduced (cut back) after the stream reaches the end of the field. The optimal furrow advance rate is one which minimizes the sum of deep percolation and runoff losses. This is commonly estimated to be where the total advance time (for the stream to initially reach the end of the furrow) is approximately one-fourth the length of set (e.g., 5 to 7 hours for a 24-hour set). An alternative approach is to use cut-back irrigation, where a large stream size is used to push the stream through to the end of the furrow in minimal time, and then the stream size is cut back to minimize runoff and erosion.

The length of an irrigation furrow from top to bottom of the field is termed the length of run. The shorter the length of run, the shorter the furrow advance time, other factors being held constant. Use of a shorter length of run also allows the use of a smaller stream size, which implies a slower furrow advance rate and reduced runoff losses. Hence, the use of a shorter length of run can reduce deep percolation and runoff, and result in greatly increased irrigation efficiency. Labor costs are increased, however, due to the need for changing sets more frequently, the use of more tubes per irrigation set, and longer tillage, planting, and application operations because of more frequent tractor turn-arounds.

Some Current and Proposed Irrigation Systems

According to Gossett (1975), farmers in the Yakima Valley of central Washington did not know in the early 1970's with any certainty how much water was being applied in a given irrigation.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

They typically applied water in 24-hour sets, often neglecting irrigation in order to perform more critical farming operations. Most irrigating was done on the basis of fixed rotation or visual crop symptons, rather than by scheduling the irrigation to meet predicted crop demands. Irrigation scheduling has been actively researched and promoted by USDA personnel at the Snake River Conservation Research Center near Twin Falls, Idaho, so greater understanding and awareness of this irrigation technique is probably occurring now (and especially in the southern Idaho area) than at the time of Gossett's study. Gossett's claims are still generally true throughout much of the irrigated West, however. Present furrow irrigation techniques are designated by the acronym PFRW in this report (Table 10). Improved furrow irrigation practices are designated by the acronym IRFW.

TABLE 10. SOME ALTERNATIVE IRRIGATION SYSTEMS FOR THE MAGIC VALLEY AND UMATILLA AREAS a/

Abbreviation	Name
	------------ Magic Valley ------------
PFRW	Present furrow system
IFRW	Improved furrow system
CTBK	Cut-back furrow system
PMPBK	Pump-back furrow system
GPIPE	Automatic gated-pipe system
MLTST	Automatic multi-set system
SDRL	Side-roll sprinkler system
	------------ Umatilla Area ------------
PCP	Present center-pivot system
ICP	Improved center-pivot system

a/ In each study area, the acronym BMRK refers to the benchmark farming situation, representing the current crop, soil, and irrigation system standard against which all on-farm modifications are to be compared.

EPA-287 (Cin.)
(4-76)

Additionally, Gossett found that many farmers in the Yakima Valley used a relatively small stream size in order to minimize visual runoff losses. As a consequence, they induced relatively large deep percolation losses because of nonuniform water application between head and tail portions of the field. Currently in the Magic Valley area of southern Idaho, the amounts of sediments in runoff waters and reused irrigation waters suggest that larger stream sizes, and greater amounts of runoff and erosion, are more common than in the Yakima Valley. The Magic Valley area also tends to have steeper slopes and more erosive soils, which further accentuates the erosion problem. Furrow irrigation efficiency can be improved by employing additional labor to reduce (cut back) stream size once the stream has advanced to the bottom of the field. Such irrigation is designated by the acronym CTBK (Table 10). Such an approach markedly reduces runoff losses. The initial use of a relatively large stream size also improves the uniformity of water application by reducing the period of furrow advance, so deep percolation losses are reduced as well.

With pump-back (PMPBK) furrow irrigation systems, runoff is collected from the bottom of one or more fields through the use of ponds, and is then pumped back to the top of the same or adjacent fields. Although runoff still occurs, it does not leave the farm. The collection ponds also serve as sediment ponds, from which eroded sediment can be redistributed to nearby croplands. For this study, deep percolation losses for pump-back systems have been assumed to be equivalent to those of present furrow irrigation systems. Other workers have even assumed reduced deep percolation losses from pump-back systems, reasoning that larger stream sizes could be employed since sediments are to be collected away. As pump-back systems are normally used on highly erosive fields, however, increased stream size would generally lead to excessive erosion. This in turn would produce a need for extremely large collection ponds and frequent sediment spreading operations.

Gated pipe (GPIPE) irrigation systems combine features of both the improved furrow and cut-back systems. The gated-pipe system would normally be controlled by a time clock or a master control panel. When coupled with on-demand water availability, irrigations could be scheduled according to crop needs. Length of set could be automatically controlled, so that uniform set times would no longer be required, and set length could be varied during the course of the irrigation season. Stream size could also be automatically cut back when the stream reached the end of the field.

The automatic multi-set (MLTST) irrigation system combines features of the improved furrow system with a shorter length of run, by having several lateral supply pipes across a given irrigated field. Irrigations can be started automatically by time clocks or a master control panel. They can also be scheduled to meet crop needs. Lengths of set can be automatically controlled, and the shorter length of run reduces the period of furrow advance. This in turn increases uniformity and decreases deep percolation. Additionally, a shorter length of run allows for the use of a smaller stream size, which reduces runoff. The reader is referred to Worstell (1976) for a more complete description of such systems.

Farmers using sprinkler irrigation systems (and especially center-pivot systems) commonly over-irrigate early in the season to promote deeper root growth, in case of a subsequent breakdown in the sprinkler system or a period where evaporative demand exceeds system capabilities. Early season irrigation is also used as a means of wind erosion control. Late season over-irrigation and leaching often result from a reluctance to decrease water application following hot summer months as rapidly as plant water needs fall off. In view of these practices, and the fact that the predominant soil texture in areas where center-pivot irrigation predominates (such as the Umatilla, Oregon, area) is often a fairly coarse sand, excessive deep percolation is common. Common sprinkler irrigation systems will be designated (Table 10) by the acronyms SDRL (for side-roll), PCP (for present center-pivot), and ICP (for improved center-pivot) systems.

Furrow Irrigation Efficiency

Estimates of furrow irrigation efficiency have been made by various authors (Whittlesey and Allison, 1971; Gossett, 1975; Kraft, 1975; Fitzsimmons et al., 1978). Table 11 lists values selected for this study. Acronyms used in the table are defined in Table 10. Attention should be focused on the column headed "PFRW," which refers to estimated efficiencies for current furrow-irrigated crops in the Magic Valley area of Idaho. In general, they are similar to the "Improved Management" efficiencies proposed by Gossett in 1975, though rounded to the nearest 2.5 percent. These values are approximately in the mid-range of all estimates from the above studies, and reflect the judgment that irrigation efficiencies should have improved somewhat since the late 1960s, the period for which Gossett compiled estimates of then-current irrigation efficiencies in the Yakima Valley of Washington. Only in the case of potatoes was Gossett's "Improved Management" efficiency estimate rejected as being too optimistic for a present-day furrow-irrigated crop.

From the definition of on-farm efficiency, the total water lost as runoff and deep percolation under furrow irrigation is given by:

$$TL = R + P = 100 - E$$

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EPA-287 (Cin.)
(4-76)

TABLE 11. ESTIMATED IRRIGATION EFFICIENCIES FOR MAJOR CROPS AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY[a]

Crop	Irrigation system[b]						
	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	(percent)						
Alfalfa	57.5	62.5	72.5	77.1	77.5	92.5	75
Small grains	50	55	65	66.7	70	85	70
Pasture	50	55	65	67.6	70	85	70
Peas	47.5	52.5	62.5	62.7	67.5	82.5	62.5
Field corn	45	50	60	69.2	65	90	72.5
Sugarbeets	45	50	60	69.2	65	90	72.5
Dry beans	37.5	42.5	52.5	57	57.5	82.5	62.5
Potatoes	32.5	37.5	47.5	50	52.5	77.5	60

[a] Assumes silt loam and loam soils with 0.5 percent to 5 percent slopes.

[b] For definition of irrigation system acronyms, see Table 10.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

where TL = total water loss as a percentage of water applied; R = percent runoff; P = percent deep percolation; and E = on-farm efficiency. Thus, having an estimate of efficiency also gives an estimate of total water loss. The difficulty comes in dividing the losses between runoff and deep percolation. Estimates of runoff are at least measurable (though often not conveniently), so values of runoff will commonly be estimated from existing data and deep percolation will be taken as the remainder of the total loss value. Carter (D.L. Carter, Snake River Conservation Research Center, Kimberly, Idaho, personal communication, 1978) estimates that runoff values associated with furrow irrigation in the Magic Valley area of Idaho are typically in the range of 30 percent to 40 percent, whereas Worstell (Robert Worstell, Snake River Conservation Research Center, Kimberly, Idaho, personal communication, 1978) estimates runoff values for the same area at 20 percent for close-growing crops and 30 percent for row crops. Based on these values, runoff estimates of 25 percent and 35 percent have been used in this study for close-growing crops and row crops, respectively (Table 12). Different values could be substituted for other areas, soil types, etc.

Estimates of total water loss for our purposes were derived from Gossett's "Improved Management" efficiency estimates, as explained above. Respective runoff estimates of 25 percent and 35 percent for close-growing and row crops were then deducted to give estimates of deep percolation. Deep percolation should increase, however, as crop rooting depth (Table 6) decreases. It was necessary to adjust some of the efficiency values by 2 to 6 percent in order to yield this desired relationship with crop rooting depth. The efficiency estimates were adjusted, instead of the runoff values, because less confidence was associated with the efficiency estimates.

Efficiency values for an "improved" furrow-irrigation system (IFRW) were obtained by adding estimates of the changes in efficiency associated with improved management practices. Gossett's data showed a corresponding average increase in efficiency for various crops of approximately 9 percent. However, Gossett's data base was from the late 1960's. Since then, substantial improvements have occurred in furrow-irrigation management. Therefore, 5 percent was added to each present furrow efficiency value in order to arrive at a corresponding efficiency value for an "improved" furrow system (Table 11). Since the efficiency was assumed to be 5 percent greater, the total loss must be 5 percent less. It was assumed that the decrease in losses was divided evenly between runoff and deep percolation (Table 12).

Efficiency values for the cut-back system (CTBK) were estimated in the same manner. Gossett estimated an average increase in efficiency of 18 percent due to use of the cut-back

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EPA-287 (Cin.)
(4-76)

TABLE 12. ESTIMATED PERCENT RUNOFF AND DEEP PERCOLATION FOR MAJOR CROPS AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY[a]

	Irrigation system[b]						
Crop type	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	- - - - - - - - - - - - - Runoff (%) - - - - - - - - - - - - - - -						
Row	35	32.5	25	0	22.5	5	0
Close-growing	25	22.5	15	0	12.5	5	0
	- - - - - - - - - - - - Percolation (%) - - - - - - - - - - - -						
Alfalfa	17.5	15	12.5	22.9	10	2.5	15
Small grains	25	22.5	20	33.3	17.5	10	20
Pasture	25	22.5	20	33.3	17.5	10	20
Peas	27.5	25	22.5	37.3	20	12.5	27.5
Field corn	20	17.5	15	30.8	12.5	5	17.5
Sugarbeets	20	17.5	15	30.8	12.5	5	17.5
Dry beans	27.5	25	22.5	43	20	12.5	27.5
Potatoes	32.5	30	27.5	50	25	17.5	30

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[a] Assumes silt loam and loam soils with 0.5 percent to 2 percent slopes.

[b] For definition of irrigation system acronyms, see Table 10.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

technique. Because improvements have occurred since that time, a value of 15 percent increase in efficiency was used for this study (Table 11), with 10 percent of the increase attributed to decreased runoff losses and 5 percent to decreased deep percolation (Table 12).

Changes in efficiency and losses for the gated-pipe (GPIPE) system were assumed to be the sum of those for the improved furrow and cut-back systems, since the gated pipe system has features of each. Therefore, irrigation efficiency, runoff, and deep percolation for this system were estimated to be 20 percent greater, 12.5 percent less, and 7.5 percent less, respectively (Tables 11 and 12).

For the multi-set (MLTST) irrigation system, according to Worstell (1976), irrigation efficiencies above 90 percent are possible. In order to achieve at least this level for several crops, 35 percent and 45 percent were added to efficiency values of the percent furrow system for close-growing and row crops, respectively (Table 11). Runoff losses for mutli-set systems were estimated to be 5 percent of the water applied, with deep percolation assumed to account for the remainder of the losses (Table 12).

Sprinker Irrigation Efficiency Estimates

Estimates of irrigation efficiencies for various crops when using side-roll sprinkler systems were given by Gossett (1975) and Kraft (1975). These estimates are based upon Bureau of Reclamation data from central Washington. Generalized efficiency estimates for side-roll (SDRL) and center-pivot (PCP) sprinkler systems common to the Pacific Northwest have been given by Chen et al. (1976), Gossett and Willett (1976), King et al. (1977), Busch (1978), and Shearer (1978). These estimates for side-roll systems range from 65 to 75 percent, which is close to Gossett's range of 59.3 to 74.7 percent. On this basis, Gossett's estimates for a well managed side-roll system were felt to be representative of irrigation efficiencies attainable with such a system. They have been rounded to the nearest 2.5 percent and used as the efficiency estimates for this study (Table 11). Runoff losses from sprinkler-irrigated fields have been assumed to be zero, and 10 percent of the applied water has been estimated to be lost as spray evaporation and wind drift. Deep percolation for the sprinkler systems has been estimated by deducting wind and evaporative losses from total losses (Table 12).

For center-pivot irrigation systems currently being used in the Pacific Northwest, unique irrigation efficiency values are not normally given for each crop. Differences between crops are generally assumed to be small and would primarily reflect differences in rooting depth superimposed on the nonuniformity

EPA-287 (Cin.)
(4-76)

of sprinkler application. Such interaction would lead to localized leaching in portions of the field receiving more water than the crop can use subsequently. The efficiency of sprinkler-irrigation systems is much more dependent on system design characteristics (as opposed to crop characteristics) than is true for furrow-irrigation systems. The range in estimated efficiency values for center-pivot system is commonly from 75 to 85 percent. For this study, an efficiency value of 80 percent was assigned to center-pivot systems presently used in the Pacific Northwest. Field runoff was assumed to be zero for such systems (though considerable localized runoff can occur), and spray evaporation and wind losses were assumed equal to 10 percent. The remainder of the losses (i.e., 10 percent) were attributed to deep percolation. A value of 5 percent was assumed as the improvement in efficiency to be realized as improved management techniques are applied to center-pivot systems (acronym ICP, see Table 10). Similarly, deep percolation losses for improved center-pivot systems were assumed to equal to 5 percent. Spray evaporation and wind losses were assumed to remain unchanged.

Effect of Texture and Slope on Irrigation Efficiency

Since various soil textures exist throughout the Pacific Northwest, it is necessary to have some feeling for the effects of soil texture on irrigation efficiency, runoff, and deep percolation. Such effects have been dealt with by the Soil Conservation Service (1973), Gossett (1975), and Hagan (1978).

Gossett's estimates of furrow irrigation efficiencies claimed greater losses for more coarse-textured soils. However, runoff losses generally decrease for coarse-textured soils, which tends to offset the increase in deep percolation. The Soil Conservation Service (1973) and Hagan (1978) estimates apparently already took into consideration these offsetting trends, for no soil texture-dependence of furrow irrigation efficiencies was proposed. Because we felt that the increase in deep percolation was greater than the decrease in runoff as more coarse-textured soils were irrigated, a 5 percent decrease in furrow irrigation efficiency was assumed in this study for sandy loam soils compared to their silt loam counterparts. This relatively minor change in irrigation efficiency would not even be significant in many real-world situations. For sprinkler irrigation systems, all authors agreed that lower efficiencies result when more coarse-textured soils are irrigated. Five percent less irrigation efficiency has been assumed in this study for sprinkler-irrigated sandy loams, than for their silt loam counterparts.

The net effect of the above adjustments is an assumption of 5 percent less efficiency when irrigating sandy loam soils than when irrigating silt loam soils. Deep percolation values for

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

sandy loams are also assumed to be 5 percent greater than for silt loams. No adjustment of surface runoff values is assumed to be required for this particular change in soil texture. For other soil texture changes, different variations in irrigation efficiency, deep percolation, and runoff losses may be required.

It is also frequently necessary to estimate the effects of field slope on irrigation efficiency, runoff, and deep percolation losses. Slope-dependent adjustments in irrigation efficiency have been suggested by the Soil Conservation Service (1973) and by Hagan (1978). The values suggest that efficiency generally decreases as slope increases. Control of furrow stream size is more difficult on steeper slopes, and the grower tends to be generous in the stream size allocated. Hence, the percent runoff tends to increase. The stream also tends to run faster on steeper slopes, however, resulting in a smaller wetted furrow cross-section. This should decrease deep percolation losses. For this study, furrow irrigation efficiency was assumed to remain unchanged in going from a 0.5 to 2.0 percent slope class to a 2 to 5 percent slope class. Similarly, no adjustment in sprinkler irrigation efficiency was felt necessary for this particular change in slope class. Runoff and deep percolation values for the base level (0.5 to 2 percent slope class) conditions in our study areas (Table 12) were respectively increased by 5 percent and decreased by 5 percent for furrow irrigation of fields having slopes in the 2 to 5 percent slope class. No change in deep percolation or runoff losses was adopted for this particular change of slope on sprinkler-irrigated fields.

Net Irrigation Requirements

Consumptive use is defined as the amount of water transpired during plant growth plus that evaporated from the soil surface and foliage in the area occupied by the growing plant (Sutter and Cory, 1970). The net irrigation requirement is commonly defined as crop consumptive use less seasonal precipitation (Watts et al., 1968). It does not consider moisture stored in the root zone at the beginning of the growing season. As a result, estimates of net irrigation requirement somewhat overstate crop seasonal needs for irrigation water, especially if "deficit" irrigation (using previously-stored soil moisture) is being practiced. Net irrigation requirement estimates were used for this study.

Net irrigation requirements have been estimated for some of the major crops grown in each of our Pacific Northwest study areas. Sutter and Cory's (1970) values for the Magic Valley area of Idaho were based upon a modified Blaney-Criddle procedure which considers mean daily temperature, hours of daylight, and crop characteristics. Based on climatological data for this area, Sutter and Cory produced three types of estimates: mean

EPA-287 (Cin.)
(4-76)

seasonal net irrigation requirements, values for the eighth driest year out of ten, and the maximum net irrigation requirement for the period of record.

According to Wright (James Wright, Snake River Conservation Research Center, Kimberly, Idaho, personal communication, 1978), the Blaney-Criddle method underestimates crop consumptive needs because the formula underestimates evaporation. This underestimation occurs because differences in elevation are not considered (with more evaporation occurring at higher elevations) and also because the method uses mean daily temperatures, which include nightly temperatures. Daytime temperatures alone largely determine the amount of evapotranspiration, because plant stomates close at night and evaporation becomes minimal. Wright has also estimated net irrigation requirements for several crops grown in the Magic Valley area.

The present study makes use of Wright's irrigation requirement estimates for alfalfa, spring grain, peas, and dry peas in the Magic Valley area (Table 13). As Wright did not at the time have estimates for the other major crops of the area, Sutter and Cory's estimates of maximum net irrigation requirement for the period of record were used. These values agreed most closely with Wright's estimates for the four crops listed above. Sutter and Cory's estimate for late potatoes was also used in lieu of Wright's estimate, since it was believed to be more realistic. It is unclear why Wright's value was so low for this particular crop.

For the Umatilla area of Oregon, Vomocil's (1976) estimates for the eighth driest year out of ten have been used, since they came closest to counterpart values for the Magic Valley area (Table 13). No data for maximum net irrigation requirement for the period of record were available in this case.

Estimates of Water Application Requirements

Irrigation efficiency (E) is the percent of applied water which remains in the crop root zone, whereas net irrigation requirement (Q_c) is the amount of water that should be in the root zone in order to meet crop needs. Therefore, the water that must be applied to a field (Q_a) in order to meet crop needs is:

$$Q_a = Q_c/(E/100).$$

Once estimates are available of the quantity of water applied and of the percent runoff and deep percolation, it is possible to obtain estimates of the amounts of runoff and deep percolation by simply multiplying the appropriate terms together.

To estimate efficiency, deep percolation, and water application requirement values for pump-back irrigation systems

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PAGE NUMBER

EPA-287 (Cin.)
(4-76)

TABLE 13. SEASONAL NET IRRIGATION REQUIREMENTS FOR MAJOR CROPS IN THE MAGIC VALLEY AND UMATILLA AREAS

Crop	Magic Valley	Umatilla Area
	- - - - - (inches/acre)[a]	- - - -
Alfalfa	37	41
Spring grain	22	---
Winter grain	25	25
Pasture	25	---
Peas	16	---
Field corn	22	29
Sugarbeets	29	---
Dry beans	20	21
Early potatoes	---	28
Late potatoes	26	37

[a] 1 inch = 2.54 cm.; 1 acre = 0.405 hectare.

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EPA-287 (Cin.)
(4-76)

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which were not dealt with earlier in this section), quantities of deep percolation (Q_d) were assumed to be equivalent to those for the present furrow system. These estimates were added to the net irrigation requirement (Q_c) values in order to obtain water requirement values (Q_a) for the pump-back system. Hence,

$$Q_a = Q_c + Q_d.$$

Efficiency values for the pump-back system (E) were then obtained as

$$E = Q_c/Q_a.$$

Values for percent deep percolation from the pump-back system (P) were obtained as

$$P = 100 - E,$$

because runoff for the pump-back was assumed equal to zero.

SEDIMENT AND PHOSPHORUS LOSSES (BACKGROUND)

Most phosphorus (P) lost from irrigated croplands is associated with eroding sediments. This section will dwell primarily on factors affecting the erosion of sediments. Important variables affecting erosion will be separated whenever possible, to permit assessment of their independent effects. Estimation of sediment contents will be introduced near the end of the section.

Slope and Stream-Size Effects

The dynamics of soil erosion during furrow irrigation have been investigated on numerous occasions. The relation of stream size and furrow slope to soil erosion was examined by Gardner and Lauritzen (1946), Israelsen et al. (1946), Evans and Jensen (1952), Mech (1959), and Fitzsimmons et al. (1978). Recalculation of results from the above studies in each case showed a dependence of erosion on field slope raised to a power between 1.5 and 2.7, other factors being held constant. Evidence for a slope-soil texture interaction was reported by Israelsen et al. (1946) but will be ignored for this study. A separate soil texture correction factor will be applied instead. The average slope dependence of erosional losses for all of the above studies varied as the $(\text{slope})^{2.2}$. So that a false sense of accuracy (and hence authenticity) is not bestowed on the relation, a dependence on $(\text{slope})^2$ has been assumed for the purposes of our study.

Effects of furrow stream size on soil erosion losses have been reported by Evans and Jensen (1952), Mech (1959), Carter

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3/8"
PAGE NUMBER

EPA-287 (Cin.)
(4-76)

(1976), and Fitzsimmons et al. (1978). Workers for the Soil Conservation Service (1973) stressed the concept of "maximum nonerosive stream size," but Carter (D.L. Carter, Snake River Conservation Research Center, Kimberly, Idaho, personal communication, 1978) reported significant erosion even at 5 percent runoff for some fields in the Magic Valley area. Appreciable sediment deposition may occur in the center of the field, however, and may offset such erosion on a field-wide basis. Actual erosion losses from many irrigated fields may be primarily from the bottom third of the irrigation run. In the Boise Valley, Fitzsimmons et al. (1978) reported that doubling the stream size (but maintaining the same amount of water applied) approximately doubled the amounts of surface runoff and sediment lost. This would generally be an unrealistic approach, however, for irrigation is usually maintained for a specified set time (often 24 hours) rather than for a specified quantity of applied water. Doubling both the stream size and the total amount of water applied increased sediment losses four-fold in this same study [i.e., sediment loss depended on (stream size)$^{2.0}$ under more normal operating conditions.] Stream-size or percent-runoff dependence of erosional losses in the above studies ranged from the 1.0 power (a linear dependence) to the 3.6 power. The exponents averaged 2.3. As with the previous treatment of slope/erosion interactions, to avoid conferring a false sense of accuracy and in the absence of more definitive data, a dependence on (stream size or runoff volume)$^{2.0}$ has been assumed for the purposes of this report.

Tillage and Set-Time Effects

The relation of freshly disturbed furrows to erosion losses has been demonstrated experimentally (Evans and Jensen, 1952). Greater than ten-fold decreases in erosion were noted by Mech and Smith (1967) between initial and subsequent irrigations following reditching operations. Similarly, Fitzsimmons et al. (1978) reported that over one-third of the seasonal sediment loss can occur during a single preplant irrigation, and that loss from a seed corn field (which was cultivated several times) was over 50-fold the loss from an alfalfa field (which was cultivated very little). Brown et al. (1974) reported sharply reduced erosional losses after weeding and refurrowing of row crops were stopped in the Magic Valley area of southern Idaho. Unfortunately, cultivation between irrigations is often necessary to break surface crusts and to maintain adequate soil intake rates.

To account for tillage effects on erosion losses from irrigated fields, the approach of Gossett (1975) has been used. Gossett assumed that erosion losses for each of the first three irrigations of a potato field in the Yakima Valley of Washington were 3.1 times the losses from the next three (mid-season) irrigations, because of tillage preceding each early-season

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

irrigation. He also assumed that sediment losses during each late-season irrigation were only 15 percent of those during each mid-season irrigation. This approach, though qualitatively correct in many situations, requires adjustment if a given crop has different numbers of irrigations following tillage operations than assumed by Gossett. For a wheat crop, for example, only one "early-season" irrigation (i.e., following a tillage operation) might be assumed, with remaining irrigations then assigned to the "mid-season" and "late-season" modes. Of course, some such differences are already inherent in crop-type erosion variations, but they have been assumed separable here to more accurately deal with a wider range of growing conditions.

Mech (1959) also reported that 78 percent of the total sediment (22.7 t/acre or 50.9 mt/ha) lost from a section of recently-cultivated furrows during a 24-hour irrigation was lost during the first 32 minutes of runoff, and that virtually all of this sediment was lost in the first four hours of irrigation. This was true even though flow slowly increased during the irrigation set because of decreasing soil intake rate. Because of such trends, Carter and Bondurant (1977) claimed that less erosion should occur from fields that were irrigated longer and less frequently, though such an approach might increase leaching losses and could be impractical for shallow-rooted crops. As no set-length dependence of erosion losses was assumed for this study, a relatively constant distribution of sediment losses with time during any given irrigation is inherent to our approach. A set-length dependence of erosion losses is a refinement which is badly needed in many situations.

Soil Texture Effects

Soil texture is another important variable affecting sediment erosion losses from irrigated lands. Pfeiffer (1975) approached this variable through the use of soil erodibility ("K") factors from the Universal Soil Loss Equation (USLE) (Stewart et al., 1975). The soil erodibility factor is merely one of a series of multiplicative terms from which erosion losses for nonirrigated areas have been estimated. This equation was originally developed in the midwestern United States for describing soil erosion during rainfall events. Appropriate soil erodibility values have been obtained from nomographs in the report of Stewart et al. (1975). Inputs to the nomographs in this case included: (1) percent silt plus very fine sand, and percent sand. These were estimated from the midpoint of a Soil Conservation Service (SCS) textural triangle for each soil textural class; (2) one percent organic matter (typifying the arid conditions under which most irrigated lands of the Pacific Northwest have developed); (3) a medium to coarse granular soil structural class; and (4) a "moderate" permeability class. Resultant "K" values are 0.48 for silt loams, 0.28 for loams, 0.22 for silty clays, 0.18 for sandy loams, and 0.09 for loamy sands. These values are assumed proportional to sediment loss from the respective soil types. Workers for the Soil Conservation Service have developed "K" values for many specific soil series in the Pacific Northwest, based upon more precise soil texture, organic matter, structure and permeability information. Refinements will eventually be necessary. Silt loams in the Yakima Valley are reportedly less erosive than silt loams in the Twin Falls area, for example (D.C. Larsen, University of Idaho, Boise, personal communication, 1978). Soil-series-specific "K" factors may help in this regard, but the "K" factors listed above have been used in assigning relative erosion values to different soil textural classes considered for this report.

Crop Effects

Crop type is an extremely important variable affecting soil erosional losses. Gossett (1975) reported relative sediment losses from row crops which were three- to ten-fold greater than those from close-growing crops. Other crop-type erosion data have been provided by Mech (1959) and by Fitzsimmons et al. (1978). The latter studies were particularly useful for this study, because they dealt specifically with the southern Idaho area. For the economics portion of the Fitzsimmons et al. (1978) study, potatoes were assigned a sediment loss of 18.0 t/a (40.3 mt/ha); corn, beans and sugarbeets were assigned a value of 3.6 t/a (8.1 mt/ha); small grain and peas were assigned a value of 1.4 t/a (3.1 mt/ha); and alfalfa was assigned a value of 0.4 t/a (0.9 mt/ha). Part of the fields used for assignment of these averages appear to have been fields to which some control structures (filter strips, tee slots, etc.) had already been applied, however. Based once more on a "limited accuracy" approach merging the Gossett (1975) and Fitzsimmons et al. (1978) data, potatoes were assigned an average sediment loss of 18 t/a (40 mt/ha), with other row crops assigned a sediment loss value 40 percent as large (7.2 t/a or 16 mt/ha), and with close-growing crops assigned a sediment loss value only 5 percent of that assigned to potatoes (0.9 t/a or 2 mt/ha).

The high erosional losses from furrow-irrigated potatoes may soon become a thing of the past, as most potato acreage becomes irrigated by sprinkler methods. It has been estimated, for example, that 85 percent to 90 percent of the potatoes in Idaho are now sprinkler-irrigated (D.C. Larsen, University of Idaho, Boise, personal communication, 1978). This is a fortunate trend, for furrow-irrigated potatoes are particularly erosive because of the large stream sizes and frequent irrigations which are employed. Conversion to sprinkler irrigation also generally means that the land is better managed, with less erosion in the spring and a greater savings of time and water during the early crop season.

As greater refinement of the data evolves, beans should

EPA-287 (Cin.)
(4-76)

probably be delineated as potentially more erosive than other row crops. Spring wheat and new alfalfa should also be delineated as slightly more erosive, and hops as slightly less erosive, than their respective groups. Breakdowns of crop loss values such as listed above are probably all that can be justified from the present degree of knowledge, however.

Phosphorus Losses

Loss of total phosphorus is generally correlated with sediment loss, since much of the phosphorus is attached to eroding soil particles. Fitzsimmons et al. (1978), for example, found a correlation coefficient of 0.8 between total phosphorus and suspended solids. Only negligible amounts of phosphorus, in comparison, are generally leached through soil in percolating waters, and no apparent relation exists between soluble orthophosphate and sediment concentrations of runoff waters (Carter et al., 1976). Greater amounts of phosphorus appear to be associated with a given weight of fine sediments (e.g., clay and silt-sized) than with the same weight of coarse sediments (e.g., sand-sized). For example, coarse sediments are more readily retained by sediment ponds, whereas fine sediments tend to remain in suspension and to be transmitted through such ponds. As a result, Carter et al., (1974) reported that retention basins removing 65 to 75 percent of the sediment from runoff waters removed only 55 to 65 percent of the total phosphorus. Similarly, for sediment ponds removing 82 to 91 percent of runoff-water sediments, Fitzsimmons et al. (1978) found phosphorus-removal levels of only 35 to 78 percent. The amounts of phosphorus eroded should also depend on the previous fertilization history of the field, on the method of most recent fertilizer phosphorus application (e.g., banded versus broadcast), and upon the soil organic matter content.

Carter et al. (1974) summarized a large number of sediment and phosphorus loss data for two of the main irrigated tracts in the Magic Valley area of southern Idaho. Total phosphorus losses in their studies averaged 0.14 percent of total sediment losses. This amounts for 2.8 lbs. of total phosphorus lost per ton of eroded sediment (1.4 kg/mt). These data were from one of the two study areas used for the economic portion of this report. Furthermore, the other area, near Umatilla in northeastern Oregon, was modeled as a predominantly sprinkler-irrigated setting, with negligible sediment and phosphorus losses. Hence, the average phosphorus:sediment ratio found by Carter et al. (1974) has been used for this report. The ratio is probably of sufficient accuracy for many other Pacific Northwest irrigated areas as well. Site-specific relations between sediment and total phosphorus are desirable whenever such are available, however.

This method of estimating phosphorus loss ignores the

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

difference in fertilization rates between crops. At the present time, adequate data are not available to allow such a distinction, though future research should cast additional light on this problem. Similarly, no attempt was made in this study to subdivide eroded phosphorus into soluble, "available" (extractable), or nonextractable forms, because of the poor correlation reported by Carter et al. (1974) when such attempts were made. Recent success in relating easily-measured sedimentation rates (Imhoff cone readings) to sediment losses in central Washington (L.G. King, Washington State University, Pullman, personal communication, 1978), combined with turbidity readings to characterize the proportion of finer sediment, may eventually permit more precise relation of sediment loss to the loss of different soil phosphorus fractions. Such refinements are beyond the scope of the present study, however.

Verification

Data with which to verify the sediment loss model are limited. Figure 4 summarizes a comparison of predicted sediment loss values (using the above approach) with measured sediment loss values. Agreement is reasonably good, with a correlation coefficient between the two sets of parameters of 0.85 and a slope of 1.11. This is not really a valid "verification" of the predictions, however, for the Fitzsimmons et al. (1978) data were a major part of the data base used to develop the predictive model. Columbia Basin data from the Washington State University Block 86 study (constituting five of the 15 data points in the figure) provide a degree of independent verification.

Unpublished data presented by D.L. Carter at the 1979 meetings of the American Society of Agronomy in Ft. Collins, Colorado provided an additional opportunity to verify the predictive model. Measured sediment loss values for six fields studied by Carter were 37.0, 5.4, 23.0, 3.1, 141.0 and 4.9 mt/ha, with corresponding predictions from the model of 36.8, 12.2, 17.9, 6.9, 93.4 and 13.9 mt/ha. This yields a slope of 0.61 between measured and predicted values (compared to a slope of 1.0 if there were exact agreement between the two data sets), and a correlation coefficient (r value) of 0.993. Omitting the field from which sediment loss was the greatest, because of its dominance of regression relationships, a slope of 0.73 and an r value of 0.941 results. There remains considerable room for improvement in the sediment loss estimates, and yet they seem to consistently be of proper magnitude and well correlated with measured sediment loss values.

NITROGEN LOSS (BACKGROUND)

Most nitrogen loss from irrigated croplands is associated with deep percolation. Unless nitrogen has been metered into

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(4-76)

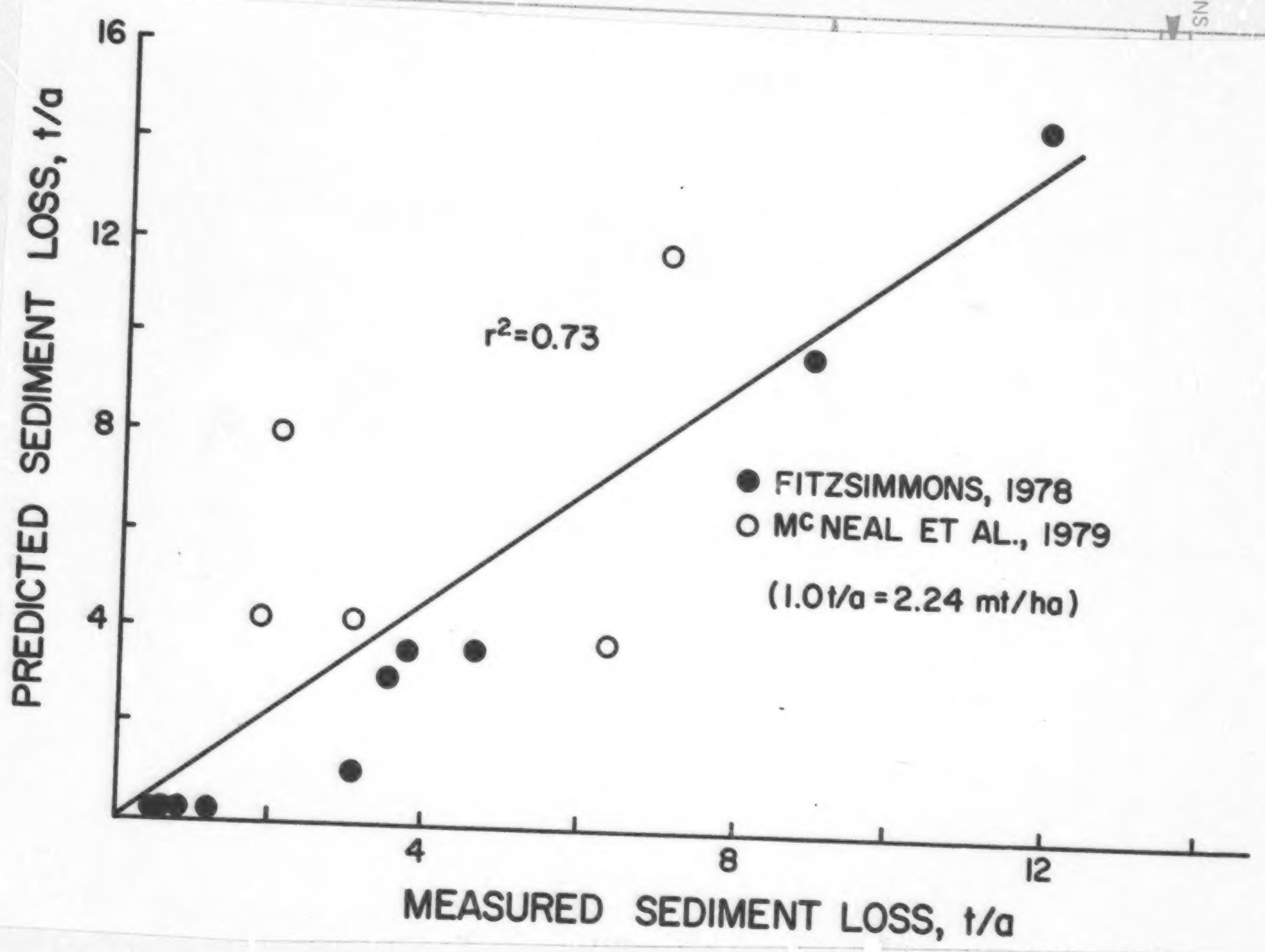

Figure 4. Comparison of predicted and measured sediment losses from some Pacific Northwest irrigated lands.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

the irrigation water, levels of soluble nitrogen in surface runoff are essentially equal to the background levels of the corresponding irrigation waters. Small amounts of total nitrogen are also associated with eroding sediments, because of sediment organic matter and exchangeable ammonium contents, and comingled crop residues. Some of this nitrogen may eventually be converted to soluble form, and used to support the growth of aquatic weeds. The main concern is the non-absorbed nitrate form, however, because of its ready mobility and its reported linkage to methemoglobinemia in infants.

Limiting nitrate losses from soils is important for several reasons: 1) nitrogen is applied to cropland to increase yields, but that goal becomes expensive if nitrogen is lost prior to crop use; 2) nitrate contamination of groundwaters and surface waters may result in health hazards for infants who consume such waters; 3) nitrate contamination can be aesthetically displeasing if nutrient contents are sufficient to support algal blooms or other forms of eutrophication; and 4) any controllable contamination of water supplies is rapidly becoming unlawful. It is difficult to assign a dollar value to the health and environmental quality effects of nitrogen lost from croplands. These costs must also be weighed against the costs of controlling nitrogen losses.

9-1/8"

The quality of nitrate leached below the root zone (and hence unavailable for crop use) is dependent upon the volume and nitrogen concentration of the drainage water. Limiting nitrate losses from soils may therefore be approached in two ways: 1) by reducing the volume of drainage waters, and/or 2) by reducing the nitrate concentrations of those waters.

Nitrogen Budgets

In a controlled situation, the amount of nitrogen added to soils each season is reasonably well known. Fertilizer inputs are a matter of record. Biological nitrogen fixation can be estimated from published work with the crops being grown or from ethylene reduction assays. In much of the arid West, where little native soil organic matter is present, net mineralization is often assumed equal to zero. Denitrification (conversion to gaseous N_2 or N_2O) is not so easily determined, however. Most attempts to quantify denitrification in the field have utilized a nitrogen budget, attributing to denitrification that portion of the total nitrogen losses not accounted for by other mechanisms. Such a budget can be represented by the relation

$$N_o + N_a + N_m + N_f = N_c + N_s + N_i + N_v + N_l + N_d$$

with all values in lb/acre or kg/ha, where, N_o = initial soil nitrogen; N_a = applied nitrogen; N_m = mineralized nitrogen; N_f = fixed nitrogen; N_c = nitrogen removed with the crop;

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

N_s = nitrogen remaining in the crop root zone; N_i = nitrogen immobilized in organic form; N_v = fertilizer nitrogen volatilized; N_l = nitrogen leached below the crop root zone; and N_d = nitrogen denitrified.

Nitrogen leaching from the crop root zone can be limited by reducing the amount of nitrogen applied, increasing the amount of denitrification, or reducing the quantity of leaching water.

The steps to be taken in reducing agricultural nutrient loads of surface and groundwater differ, depending upon the ultimate fate of the drainage waters. If the drainage waters are being returned to a surface waterway, the concentration of nitrate in the receiving water is kept lowest by reducing the total amount of nitrate added. In contrast, if the drainage water percolates to a relatively stagnant or immobile aquifer, the concentrations of nitrate in the aquifer may be kept lowest by keeping the nitrate concentrations of root-zone percolates low, regardless of the total quality of nitrate added. As the quantity of percolating water increases, the total amount of nitrate removed will increase, whereas the nitrate concentrations of the drainage waters generally will decrease concurrently.

Project-Wide Studies

Studies performed to investigate nitrogen losses below the crop root zone have been conducted on three levels: 1) irrigation basin or project-wide, 2) single-field or small-plot scale, and 3) in laboratory columns. Nelson and Weaver (1971) studied the salt balance for a 70,000 acre (28,400 ha) subunit of the Wapato irrigation project, in the Yakima Valley of central Washington. The study was conducted during 1970 to 1971, with results compared to those from a similar study during 1941 to 1942. Prior to the mid-1940s, fertility was maintained with manures and with crop rotations, including legumes. By 1970, however, most fertilization was through the use of commercial fertilizers. Outputs of nitrate had increased five-fold by 1970 to 1971. Increased use of fertilizer nitrogen was thought to be the primary factor producing higher nitrogen contents of area drainage waters, but cropping changes may also have contributed to the trends. Another factor which may have accounted for some of the differences is that aquatic weeds, which can remove substantial quantities of nitrogen from the water transmission system, were more effectively controlled in 1970 to 1971.

Bingham et al. (1971) investigated nitrate-nitrogen (NO_3-N) leaching losses for a 970-acre (390 ha) watershed cropped to citrus in southern California. An average of 45 percent of the applied water was leached below the crop root zone, with NO_3-N levels of drainage waters ranging from 37 to 81 mg/l. An average of 57 lb N/acre/yr (64 kg N/ha/yr) was leached from the

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

area. Most of this resulted from the use of commercial fertilizers.

Carter et al. (1971) calculated the salt balance for a 200,000 acre (81,000 ha) irrigated tract on the Snake River Plains of southern Idaho. Though NO_3-N concentrations of surface runoff did not differ appreciably from those of the input irrigation waters (which averaged 0.12 ppm NO_3-N), subsurface drainage waters had an average NO_3-N concentration of 3.24 ppm, for an annual net loss of 30 lb N/acre (34 kg N/ha) of irrigated land. Fertilizer company records indicated that nitrogen fertilization rates for the area had averaged only 54 lb N/acre/yr (60 kg N/ha/yr) in this tract, though nearly one-half of the leached nitrogen may have arisen from alfalfa plowout instead.

Individual-Field Studies

Adriano et al. (1972a) investigated a seven-year nitrogen balance for asparagus grown on a sandy soil. They noted that NO_3-N concentrations of drainage waters were much higher at higher fertilization rates and lower irrigation levels. Denitrification was assumed to have caused greater quantities of unaccounted-for nitrogen at higher irrigation rates. Adriano et al. (1972b) found NO_3-N concentrations ranging from 50 to 120 mg/l in drainage waters under row crops fertilized at rates ranging from 145 to 560 lb N/acre/yr (162 to 627 kg N/ha/yr). They found little evidence of denitrification or net mineralization at sites characterized by open, porous soil. At sites with restricted layers in the upper portion of the profile, on the other hand, or where animal manures were used as the main nitrogen source, estimated NO_3-N concentrations were high by as much as 56 to 73 percent. Appreciable denitrification apparently occurred in each of these cases. In general, drainage water NO_3-N concentrations were found to vary directly with nitrogen fertilization rate and inversely with amount of drainage water.

Pratt et al. (1972) stated that good estimates of NO_3-N concentrations could be made if the following parameters were known: 1) excess nitrogen available for leaching (N inputs - N in the crop); 2) the volume of drainage water, which they estimated from the relative chloride concentrations of irrigation and drainage waters, assuming negligible uptake of chloride by the crop; and 3) the amount of denitrification occurring. For a sandy loam soil with no textural discontinuities (e.g., silt or clay lenses, which impede downward water movement), an approach ignoring denitrification closely estimated NO_3-N concentrations of unsaturated soil below the crop root zone. For two nearby commercial citrus groves, where the soil contained a high-clay horizon at 18 to 40 inches (45 to 100 cm), fully 50 percent of the applied nitrogen could not be accounted for by this approach. It was assumed denitrified. Estimates of soil solution

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

NO_3-N made using a mass balance approach may be too high, therefore, when textural discontinuities occur within the crop root zone. Unfortunately, such discontinuities appear to be the rule, rather than the exception, for Pacific Northwest soils.

Lund et al. (1974) found that the texture of the "profile control section" (that zone most thoroughly controlling the rate of water movement through the soil profile) influenced the volume and the NO_3-N concentrations of drainage waters. The greater the clay content of the control section, the lower the NO_3-N concentrations of the drainage waters. This is probably a direct effect on denitrification losses. Devitt et al. (1976) used changes in the chloride(Cl)/NO_3 ratio with depth below the root zone as an indicator of denitrification, in situations where Cl was not taken up by the crop. Lund and Elliot (1976) sampled sites having variable profile characteristics within a single field, and found the Cl/NO_3 ratio to be highly correlated with particle size distribution of the soil control section. Pratt (1979) found a nearly linear correlation between the saturated hydraulic conductivity of the 0 to 3 ft (0 to 1 m) section of the profile and unaccounted for nitrogen, which was presumed to have been denitrified. His correlation of soil texture with unaccounted-for nitrogen was less satisfactory than Lund and Elliott's, however.

Earlier Nitrate Leaching Estimates

In order to estimate the quantity of nitrogen being leached below the crop root zone, one needs to know the volumes and nitrate concentrations of drainage waters. A rigorous analytical approach, involving the solution of equations describing flow of water and solutes, could provide such information. In order to solve the equations, however, site-specific data which are subject to large errors and which are not yet available for many soils would be needed. Data on crop utilization of nitrogen for the large numbers of crops and growing conditions encountered throughout the Pacific Northwest would also be needed.

A comprehensive attempt to provide nitrate leaching estimates for a variety of cropping and irrigation conditions was undertaken by Regional Technical Committee W-111 ("Nitrogen in the Environment") in 1973. Members of this committee from throughout the western states were asked to provide estimates of leaching losses at five nitrogen fertilization rates for well-drained and poorly-drained soils at low, medium and high degrees of leaching. Crops included irrigated pasture, wheat, alfalfa, potatoes, and apples. Most committee members assumed that crops removed 50 to 60 percent of the applied nitrogen, and that 10 to 30 percent of the applied nitrogen was denitrified. Thus, without appreciable additions to the soil organic fraction, 10 to 40 percent of the applied nitrogen would be lost to percolating waters. Most committee members also believed that negligible

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3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

losses would be incurred from alfalfa as a living crop, although losses may be substantial after the crop is plowed under. Crop requirements for nitrogen were assumed met before either percolation or denitrification occurred.

Nitrate leaching estimates for irrigated pasture and alfalfa were generally less than 5 to 10 lb/acre (6 to 11 kg/ha). The low leaching estimates were largely a consequence of the low fertilization rates assumed for these crops. Substantially higher leaching losses were estimated for small grains, potatoes and apples. Values commonly exceeded 25 to 50 lb/acre (28 to 56 kg/ha) at the intermediate and highest leaching fractions and nitrogen application rates. A leaching loss of nearly 100 lb/acre (112 kg/ha) was estimated for potatoes under conditions of greatest leaching potential. Nitrate leaching estimates for poorly-drained soil were only about one-half as high, because of lower leaching fractions and because of the greater potential for denitrification.

Another set of generalized leaching estimates were developed by Gossett (1975) from nitrate leaching data generated by Pratt and co-workers in California. The resultant equation has been tested on a large number of southern California data, and found to rather accurately predict nitrate leaching losses for that area. The relation has the form

$$N_L = 0.42 (N_iD)^{0.712}$$

where N_L = nitrate leaching losses in lb N/acre/year, N_i = nitrogen inputs in lb/acre/year, and D = drainage water volume in acre-in/acre/year. Its metric equivalent would be

$$N_L = 0.22(N_iD)^{0.712}$$

where N_L = nitrate leaching losses in kg N/ha/year, N_i = nitrogen inputs in kg/ha/year, and D = drainage water volume in ha-cm/ha/year. In general, there is poor agreement between nitrate leaching values estimated from this equation and those estimated by members of the W-111 Regional Committee (discussed above). Nitrate leaching estimates from the regression equation were consistently the higher of the two. One explanation for this discrepancy might be that the California crops for which the equation was developed were weighted towards heavily-fertilized vegetable crops, and towards well-managed (and hence frugally-irrigated) crops, whereas the crops considered by the Regional Committee members were weighted towards less intensively-managed crops typical of the Pacific Northwest. Another explanation might be that the Regional Committee members were overly conservative in their estimates. Most had few firm field data upon which to base their opinions, and reflected a general attitude that fertilizer nitrogen is being well-managed in most crop settings. Field tests are required to ascertain

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EPA-287 (Cin.)
(4-76)

which set of predictions is more nearly correct.

Nitrogen Fertilizer Recommendations

In obtaining estimates of nitrogen leaching for irrigated portions of the Pacific Northwest, it is necessary to estimate probable nitrogen application rates for selected crop and soil settings. Nitrogen fertilization recommendations from fertilizer guides for the three Pacific Northwest states are summarized in Table 14. Actual fertilizer application may differ substantially from fertilizer guide recommendations, however. At present in the Pacific Northwest, there appears to be a consistent tendency to exceed fertilizer guide nitrogen rates in irrigated areas, as a form of "insurance" on high crop yields and because the fertilizer guides are often viewed by growers as oriented towards "average" (rather than high-level) producers.

Estimating Deep Percolation Losses

In addition to nitrogen fertilization rates, the estimated quantity of deep percolated water is generally required for nitrate leaching estimates. Such a term is explicit in equations such as Gossett's and was also included implicitly (though qualitatively) in the Regional Committee estimates. Several methods can be employed to estimate deep percolation losses. The approach recommended in this report consists of estimating deep percolation (as a percentage of water application to a given field) as the on-farm irrigation efficiency (expressed as a percentage) minus the percent runoff. Estimation of each of these parameters was dealt with in earlier portions of this chapter.

For some sprinkler-irrigated systems, deep percolation estimates can be obtained from estimates of uniformity coefficient and adequacy level (if such are available). Water distributions for three uniformity coefficient values are shown in Figure 5, for example, assuming a normal distribution of variations in water application. A field net irrigation requirement of 1 inch (2.54 cm) and a 50 percent adequacy level is shown, with only one-half of the root zone soil being returned to its maximum water-holding capacity during irrigation. Some subunits of the field (shown as 10 percent increments or 0.1-field subunits) must be over-irrigated even to meet this adequacy level. As a result, deep percolation occurs. Differences in deep percolation for the various uniformity coefficients are obvious. The tradeoff between under-irrigation and deep percolation is also apparent from the distributions. As less and less of the root zone of a field is under-irrigated, by increasing the amount of water applied to each subunit of the field (refer to Figure 6), increasing area is subjected to deep percolation. Such deep percolation carries soluble nutrients, including nitrates.

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3/8"
PAGE NUMBER

TABLE 14. TYPICAL FERTILIZER-GUIDE NITROGEN RECOMMENDATIONS FOR SELECTED CROPS GROWN IN MAJOR IRRIGATED AREAS OF THE PACIFIC NORTHWEST

Crop	Central & Eastern Washington	Western Oregon	Central & Eastern Oregon	Southern Idaho
	---------(pounds/acre)[a]	----------		
Pasture	100-200	25-35	25-35 (125-300)[c]	50-150[b]
Alfalfa hay	0[d]	0	0	0
Other hay	---	50-150	80-100	---
Winter wheat	120-200	100-200	100-150	35-120
Spring grains	130	20-50	50-150	---
Potatoes	120-320[e]	100-200	100-250	100-300
Sugarbeets	80-160	---	---	50-200
Field corn	160-240	100-200	---	100-200
Peas & beans	20-180[f]	50-150	---	25-80
Sweet corn	150-240	150-180	---	100-200
Asparagus	100	---	---	---
Tree fruits	90	100-300	100-200	---
Hops	100	---	---	---
Mint	160-240	200	---	---
Berries	35-80	35-100	---	---
Grapes	35-120	---	---	---

[a] 1 pound/acre = 1.12 kg/hectare.

[b] Highest figures for pure grass pastures.

[c] Second figure for pure grass pastures (no legumes in the mixture).

[d] Except for 60 pounds/acre annually in the Kittitas Valley, and 25-35 pounds/acre to establish new seedings.

[e] Lower values when following legumes.

[f] Higher values for lima beans and similar field beans.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

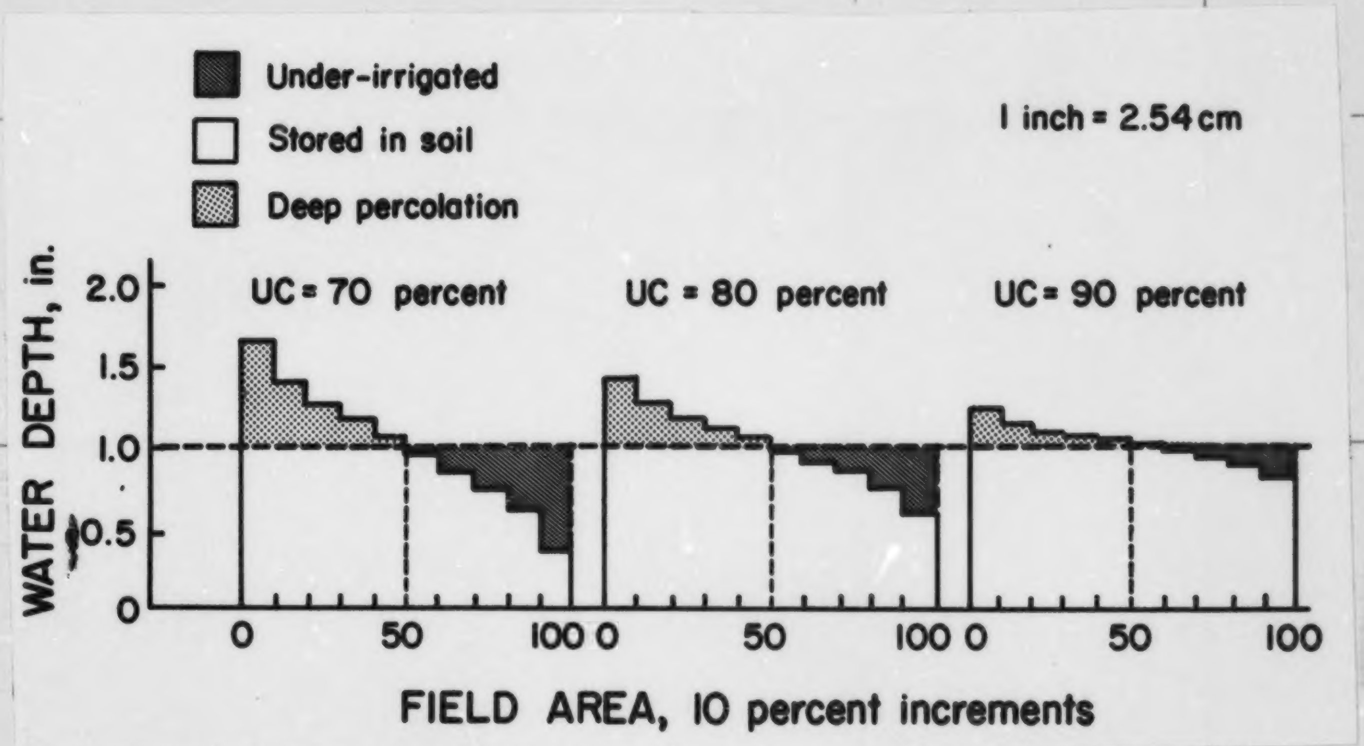

Figure 5. Water distribution for three uniformity coefficient values and 50 percent adequacy of irrigation.

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3/8''
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

As our knowledge of irrigation water distribution and soil water movement improves, the adequacy level may eventually be amenable to fairly precise estimation. It cannot be measured or even precisely estimated with current technology, however. Despite such difficulties, the adequacy level can at least be qualitatively estimated, to assist with nitrate leaching estimates. The adequacy levels considered for this study are 50 percent, 75 percent and 87.5 percent. These can be roughly equated to severely under-irrigated, "adequately" irrigated, and somewhat over-irrigated, respectively. In assigning a proper adequacy level, careful consideration should be given to portions of the field which are never irrigated to mid-row, because of convex field ends or inadequate set times. Consideration should also be given to areas evidencing reduced vegetative growth because of poorly-designed or wind-distorted sprinkler patterns.

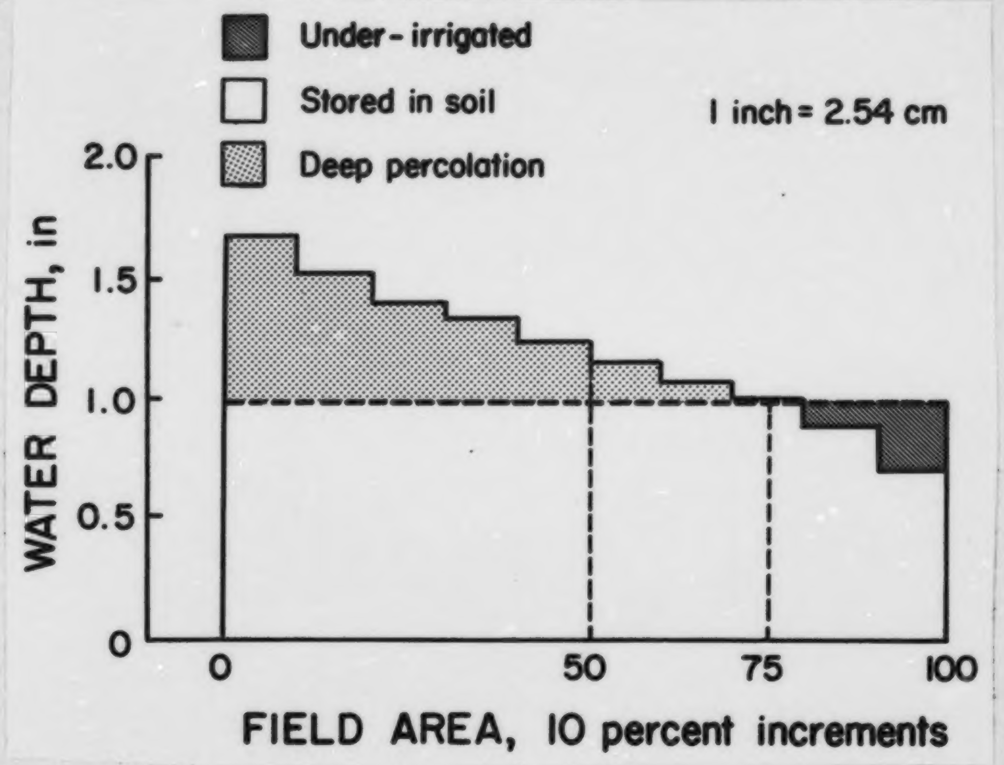

Figure 6. Water distribution with an 80 percent uniformity coefficient and 75 percent adequacy of irrigation.

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER

EPA-287 (Cin.)
(4-76)

Table 15 demonstrates the interrelationship of adequacy of irrigation, uniformity coefficient, and deep percolation values for normally-distributed water application systems. Fixing any two of these parameters automatically fixes the third. For example, uniformity coefficient estimates are commonly available for sprinkler irrigation systems. Hence, estimation of deep percolation losses is straight-forward once an adequacy level has been assigned from the above descriptive terms (under, adequately, or somewhat over-irrigated). If, on the other hand, uniformity coefficient and on-farm irrigation efficiency values are already known, an appropriate value (often 5 to 10 percent) can be assigned to wind and evaporation losses. Subtraction of this value plus the percent irrigation efficiency from 100 yields the percent deep percolation. Comparing this value with the corresponding deep percolation value from Table 15 provides an independent check on the adequacy level which should have been assigned to this field.

For furrow-irrigation systems, the unformity coefficient will commonly be unknown, though often in the range 60 to 80 percent. Estimates of on-farm irrigation efficiency (often 40 to 60 percent for furrow-irrigated fields) can be used to esti-

TABLE 15. PERCENT DEEP PERCOLATION FOR SELECTED UNIFORMITY COEFFICIENTS AND ADEQUACY LEVELS

Uniformity coefficient (%)	Adequacy level 50%	 75%	 87.5%
		(percent)	
100	0	0	0
95	2.5	5	7
90	5	10	14
85	7.5	15.5	21
80	10	21	28
75	12.5	26	35
70	15	30	42
65	17.5	36	49
60	20	41	56
55	22.5	46	63
50	25	52	70
45	27.5	58	77
40	30	62	84

Note: These values assume that the variation in water application is normally distributed. Percent deep percolation is defined as a percent of the water application requirement for a given crop-soil combination.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

mate deep percolation losses, after subtracting the percent runoff and the percent efficiency from 100. If the resultant deep percolation estimate corresponds to an unrealistic uniformity coefficient or adequacy level (Table 15), a different on-farm efficiency or percent runoff may be required to "fine tune" the deep percolation, uniformity coefficient, and adequacy level values.

As suggested from Figures 5 and 6, deep percolation estimates can also be obtained for hypothetical subunits of an irrigated field, as well as for the entire field, if water application is assumed to be normally distributed. This study makes use of such subunits, each consisting of 10 percent of the area of a given field. In so doing, it is possible to account somewhat for nonuniform application of water to the field. The exact location of each subunit within the field is not specified, but neither is it necessary. By assigning an adequacy level and uniformity coefficient, and assuming water application to be normally distributed, it is possible to estimate the amount of deep percolation or under-irrigation for each field subunit (Figure 5 or 6). Table 16 shows calculated values of deep percolation for various uniformity coefficients at three adequacy levels. Deep percolation is expressed as a percent of the average amount of water applied to the field. As a result, it is possible to have deep percolation percentages of greater than 100 percent for a given subunit. Focusing for a moment on the 75 percent adequacy level, one can see that deep percolation does not occur for subunits 8 through 10. Hence, these subunits are located in parts of the field that are considerably under-irrigated.

For furrow-irrigated fields, ridges of the crop row and the lower part of the field (especially where convex field ends occur because of prior erosion) should correspond to field subunits that are not adequately irrigated. Irrigation furrows and the upper part of the field, on the other hand, should correspond in general to subunits that are over-irrigated. For sprinkler-irrigated fields, the water application pattern is not uniform due to design problems and/or wind distortion of the designed application pattern.

Nitrogen Leaching Estimates

As water percolates below the root zone, it carries varying amounts of soluble NO_3-N. The amount of nitrate leached is a function of the amount of deep percolation and the quantity of NO_3-N in the root zone (Adriano et al., 1972a; Ayers and Branson, 1973). Nitrogen in the root zone can be assumed proportional to the amount of nitrogen fertilizer applied. Several studies have shown that excessive irrigation can decrease crop production, and a major factor in such decreases is the amount of nitrogen which has leached, curtailing nitrogen uptake by the

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BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 16. PERCENT DEEP PERCOLATION FOR TENTH-FIELD SUBUNITS AT SELECTED UNIFORMITY COEFFICIENTS AND ADEQUACY LEVELS

Uniformity coefficient (%)	Field subunit[a]									
	1	2	3	4	5	6	7	8	9	10
	- - - - - - - - 50% adequacy level - - - - - - - -									
100	---	---	---	---	---	---	---	---	---	---
95	10	6	4	2	1	---	---	---	---	---
90	21	13	9	5	2	---	---	---	---	---
85	32	20	13	8	2	---	---	---	---	---
80	43	26	17	10	3	---	---	---	---	---
75	54	32	21	12	4	---	---	---	---	---
70	65	39	25	15	5	---	---	---	---	---
65	76	46	30	17	6	---	---	---	---	---
60	87	52	34	19	6	---	---	---	---	---
55	98	59	38	22	7	---	---	---	---	---
50	110	66	43	24	8	---	---	---	---	---
45	121	72	47	26	9	---	---	---	---	---
40	132	79	51	29	10	---	---	---	---	---
	- - - - - - - - 75% adequacy level - - - - - - - -									
100	---	---	---	---	---	---	---	---	---	---
95	15	11	8	6	5	4	2	---	---	---
90	30	22	17	13	10	7	4	---	---	---
85	45	32	26	20	15	10	6	---	---	---
80	60	43	34	27	20	14	7	---	---	---
75	76	54	42	34	25	18	9	---	---	---
70	91	65	51	40	30	21	11	---	---	---
65	106	76	60	46	35	24	13	---	---	---
60	121	86	68	53	40	28	15	---	---	---
55	137	97	76	60	45	32	16	---	---	---
50	153	108	85	67	50	35	18	---	---	---
45	168	119	94	74	55	38	20	---	---	---
40	183	130	102	80	60	41	22	---	---	---

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
PAGE NUMBER
EPA-287 (Cin.) (4-76)

TABLE 16. CONTINUED

Uniformity coefficient (%)	Field subunit[a] 1	2	3	4	5	6	7	8	9	10
	- - - - - - - -87.5% adequacy level- - - - - - - -									
100	---	---	---	---	---	---	---	---	---	---
95	17	13	11	9	8	6	4	2	---	---
90	34	26	22	18	15	12	8	5	---	---
85	51	39	32	27	22	18	12	7	---	---
80	69	52	43	36	29	23	17	9	---	---
75	86	66	54	45	36	29	21	12	---	---
70	104	79	65	54	44	35	25	14	---	---
65	122	94	76	63	52	40	29	16	---	---
60	139	105	86	72	59	46	33	19	---	---
55	157	118	97	81	66	52	37	21	---	---
50	175	131	108	90	73	58	41	23	---	---
45	193	144	119	99	80	64	46	26	---	---
40	211	157	130	108	88	69	50	28	---	---

NOTE: Percent deep percolation for each tenth-field subunit is defined as a percentage of the average water application requirement for the field.

[a] Each field subunit is defined as 10 percent of the area of the field. Deep percolation for subunits 9 and 10 equals zero for all uniformity coefficients and adequacy levels listed.

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

crop (Kloster and Whittlesey, 1971; Middleton and Roberts, 1972). Gossett (1975) analyzed a large number of data generated during extensive studies of nitrate leaching by workers from the University of California. He fit the data to an empirical equation of the form

$$N_L = 0.42(N_f Q_d)^{0.712}$$

where N_L = N leached (lb/acre/season); N_f = N applied (lb/acre/season); and Q_d = depth of drainage water (in/season). The metric equivalent expression would be

$$N_L = 0.22(N_f Q_d)^{0.712}$$

where N_L = N leached (kg/ha/season); N_f = N applied (kg/ha/season); and Q_d = depth of drainage water (cm/season). This equation fit the University of California field data with an r^2 value of 0.908. This was the equation used earlier in this section to compare with nitrate leaching predictions from W-111 Regional Committee members.

The slope of the above curve does not withstand close scrutiny, for it predicts relatively less leaching of fertilizer nitrogen as the drainage water volume or the nitrogen fertilization rate is increased. The former is reasonable, for additional increments of drainage water should be increasingly less effective in leaching fertilizer nitrogen. There is only a finite quantity of nitrogen to be leached. Most careful studies, however, have found increasing proportions of fertilizer nitrogen leached as the fertilization rate is increased, rather than the converse.

As a result, Pfeiffer (1976) used the following equation to estimate nitrogen leaching, based upon the same data:

$$N_L = 0.061(N_f)^{1.05}(Q_d)^{0.7}.$$

This relation is more consistent with real-world behavior (with respect to the N_f term) than was Gossett's. The metric equivalent expression would be

$$N_L = 0.032(N_f)^{1.05}(Q_d)^{0.7}.$$

Usage of the expressions can be illustrated by a numerical example. Suppose, for example, that N_f = 100 lbs/acre (112 kg/ha), and the seasonal amount of water applied (Q_a) is 50 in (127 cm). As previously discussed, Q_d is estimated by multiplying the water application requirement by the percent deep percolation (P). Assuming P = 20 percent, Q_d = 50(20 percent) = 10 in (25 cm). The annual quantity of nitrogen leached is then

$$N_L = 0.061(100)^{1.05}(10)^{0.7} = 38 \text{ lbs/acre } (43 \text{ kg/ha}).$$

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3/8"

EPA-287 (Cin.)
(4-76)

Because of the less efficient furrow-irrigation systems in general use throughout much of the Pacific Northwest, compared to the more efficient irrigation systems (including sprinkler systems) at many of the Univerity of California study sites, direct use of Gossett's or Pfeiffer's equation generally results in overestimation of nitrogen leaching losses for most Pacific Northwest irrigated croplands. McNeal and Pratt (1978), for example, found nitrate leaching predictions from these equations to be two- to three-fold too high for the Twin Falls (Carter et al., 1973) and Wapato (Nelson and Weaver, 1971) irrigation projects. It has, therefore, been deemed appropriate to make field-subunit adjustments before applying Pfeiffer's equation, and to provide an upper limit for the amount of nitrogen that can be leached from each subunit no matter how much leaching water it passes.

Deep percolation estimates for individual 0.1-field subunits (Table 16) were used with a modified Pfeiffer equation to obtain nitrogen leaching estimates for each subunit rather than for the field as a whole. These values were then summed to obtain a value for the total quantity of nitrogen leached from the field. The equation used to obtain subunit leaching values had the form

$$N_L = 0.072(N_f)^{1.05}(Q_d)^{0.7},$$

with a metric equivalent of

$$N_L = 0.038(N_f)^{1.05}(Q_d)^{0.7}.$$

The multiplier in the equation had to be increased slightly over that of Pfeiffer's original equation in order to bring summed subunit values for the entire field into agreement with field-wide nitrate leaching values.

The first two columns of data in Table 17 present individual subunit deep percolation values required to obtain a field-wide deep percolation average of 20.5 percent (corresponding with a 75 percent adequacy level and an 80 percent uniformity coefficient) at a total water application rate of 50 in (127 cm). The next column presents the fertilizer application rate per tenth-field subunit if the fertilizer were uniformly applied, and the following column provides corresponding nitrogen leaching estimates using the equation of the preceding paragraph. The net result of the subunit approach in this case is approximately a 10 percent reduction in the estimate of nitrate leaching, when compared to the value obtained from direct use of the Pfeiffer equation (39.2 lbs N/acre or 43.9 kg N/ha).

The final columns of Table 17 provide an example that might be used to simulate furrow irrigation. Leaching of nitrogen is described by assuming that the most heavily leached subunits of

EPA-287 (Cin.)
(4-76)

TABLE 17. DEEP PERCOLATION, NITROGEN FERTILIZER APPLICATION, AND NITRATE LEACHING FOR TENTH-FIELD SUBUNITS (SAMPLE CASE)

Field subunit	Deep percolation		Subunit leaching technique		Simulated furrow leaching technique	
	Percent[a] (%)	Quantity[b] (in)[c]	Nitrogen fertilizer application[d] (lbs)	Nitrate leaching (lbs)	Nitrogen fertilizer application[d] (lbs)	Nitrate leaching (lbs)
1	60.0	30.0	10.0	8.7	1.0	0.78
2	43.0	21.5	10.0	7.0	5.0	3.4
3	34.0	17.0	10.0	5.9	11.75	7.0
4	27.0	13.5	10.0	4.9	11.75	5.9
5	20.0	10.0	10.0	4.0	11.75	4.9
6	14.0	7.0	10.0	3.2	11.75	3.7
7	7.0	3.5	10.0	1.9	11.75	2.3
8	0.0	0.0	10.0	0.0	11.75	0.0
9	0.0	0.0	10.0	0.0	11.75	0.0
10	0.0	0.0	10.0	0.0	11.75	0.0
Field-wide averages or (totals)	20.5	10.3	(100.0)	(35.6)	(100.0)	(27.9)

[a] Assumes an adequacy level of 75 percent and a uniformity coefficient of 80 percent; see Table 16.

[b] Assumes a water application requirement of 50 inches.

[c] 1 inch = 2.54 cm.; 1 pound = 0.454 kg.; 1 pound/acre = 1.12 kg/ha.

[d] Assumes a nitrogen fertilizer rate of 100 pounds per acre.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

each field are associated with the irrigation furrows. For the purpose of illustration, only one-tenth of the average rate of band-applied fertilizer nitrogen is assumed to reside in the most heavily leached subunit (e.g., within the irrigation furrow), and only one-half of the average rate of fertilizer nitrogen is assumed to reside in the next most heavily leached subunit. For the remainder of the field, the fertilizer application is then 1.18 times the average fertilization rate, so that the total quantity of nitrogen per acre remains unchanged. "Simulated-furrow" nitrate leaching values are calculated from these assumptions and the modified Pfeiffer equation. The average nitrogen leaching value is reduced 20 percent further than the average subunit leaching value of the previous column, or to approximately two-thirds of the original field-wide Pfeiffer estimate. Nitrate-leaching estimates for the most heavily leached and next most heavily leached subunits are substantially reduced by this "simulated-furrow" technique. Additional water which might pass through the soil beneath the furrows would have little effect on nitrate leaching from this system, despite the considerable influence of such additional water on Pfeiffer's original nitrate leaching estimates. The differences between nitrate leaching estimates obtained using the field-wide (original Pfeiffer), subunit and simulated-furrow estimation techniques would be magnified for large nitrogen or water application rates.

Column A of Table 18 summarizes the values discussed above (from the calculations of Table 17). Column B of the table shows the nitrate leaching estimates obtained from each of the three techniques assuming a uniformity coefficient of 55 percent, an adequacy level of 75 percent, a water application requirement of 75 in (191 cm), and a nitrogen fertilization rate of 400 lbs/acre (448 kg/ha). These values are more representative of water and fertilizer practices for furrow-irrigated potatoes. In the latter case, the subunit leaching technique reduced nitrogen loss predictions 34 percent below those of the field-wide Pfeiffer technique, with the "simulated furrow" approach reducing estimated nitrogen loss by another 11 percent (to approximately 55 percent of the field-wide Pfeiffer estimate). These percent reductions are substantially larger than the corresponding values of column A.

Leaching estimates obtained from this simplistic simulated-furrow leaching approach are probably more representative of nitrate leaching from furrow-irrigated fields of the Pacific Northwest than is direct application of the unmodified Gossett or Pfeiffer equation. Even for sprinker irrigation, estimates from the subunit leaching technique should be more representative than those obtained from the original Gossett or Pfeiffer techniques. The estimates could be improved somewhat further by more accurately adjusting the amount of fertilizer nitrogen in each sub-unit to correspond with either band or broadcast ferti-

EPA-287 (Cin.)
(4-76)

TABLE 18. A COMPARISON OF NITRATE LEACHING ESTIMATES OBTAINED FROM USE OF THREE DIFFERENT TECHNIQUES

Estimation technique	Nitrate leaching A	Nitrate leaching B
	(lbs/ac) a/	
Pfeiffer	39.2	392.6
Subunit leaching	35.6	258.2
Simulated furrow leaching	27.9	216.3

Note: Column A assumes a water application requirement of 50 in and a nitrogen fertilization rate of 100 lbs per acre, an adequacy level of 75 percent and a uniformity coefficient of 80 percent. Column B assumes a water application requirement of 75 in, a nitrogen fertilization rate of 400 lbs per acre, an adequacy level of 75 percent and a uniformity coefficient of 55 percent.

a/ 1 lb/acre = 1.12 kg/ha; 1 in = 2.54 cm.

lizer application. There is no appropriate way of telling where the most heavily leached parts of the field are in relation to the fertilizer band, however, since nonuniformities of the sprinkler system are superimposed on crop planting patterns. The only reasonable approximation of sprinkler-irrigated fields at present is to assume a uniform distribution of fertilizer nitrogen throughout each of the tenth-field subunits.

Denitrification Corrections

Denitrification is the process through which microbes reduce NO_3-N to the nitrate (NO_2-) form and ultimately to N_2 or N_2O gases. Water-saturated surface soils provide the best conditions for this process, for they contain the microbes and the energy source (soluble or solid-phase carbon) that are required. Relatively high soil temperatures also speed the conversion.

Estimates of nitrogen leaching using the techniques explained above all assume an amount of denitrification roughly equivalent to that from a uniform sandy loam under southern California conditions. For other soil types, Pratt (1979) has shown that adjustments can be made on the basis of saturated soil hydraulic conductivity values. Table 19 presents typical hydraulic conductivity (h) values and corresponding multipliers for selected soil types. The multipliers (m) were calculated using the equation

EPA-287 (Cin.)
(4-76)

TABLE 19. NITRATE LEACHING DENITRIFICATION MULTIPLIERS FOR SELECTED SATURATED HYDRAULIC CONDUCTIVITY VALUES AND CORRESPONDING SOIL TEXTURES

Soil texture	Saturated hydraulic conductivity	Multiplier
	(in/hr) a/	
Coarse sand	4.0	1.6
Sandy loam	1.6	1.0
Silt loam	0.2	0.4
Silty clay loam	0.03	0.15

Note: These multipliers are to be applied to nitrate leaching estimates for sandy loam soils in order to obtain estimates for other soil textures.

a/ 1 in = 2.54 cm.

9-1/8"

$$m = 0.8(h)^{0.5}.$$

Although data are sketchy, it appears that approximate multipliers might also be obtained from the relation m = (0.015)(percent sand) for additional soil types.

As an example, assume that the value for nitrate leaching under simulated furrow leaching (27.9 lb/acre or 31.3 kg/ha) in column A of Table 18 was actually for a uniform sandy loam. Using the appropriate multiplier from Table 19 for silt loams (0.4), the value 27.9(0.4) = 11.2 lbs/acre (12.5 kg/ha) is obtained. The estimate of nitrate leaching is now only approximately 30 percent of the value obtained using the unmodified Pfeiffer equation (column A, Table 18), with approximately 30 percent of the decrease due to adoption of the simulated-furrow leaching technique, and another 40 percent due to use of the denitrification multiplier. The net effect is values which are much more in agreement with nitrate leaching values for Pacific Northwest irrigated tracts (Nelson and Weaver, 1971; Carter et al., 1973; McNeal and Pratt, 1978) than were the unmodified Gossett or Pfeiffer estimates.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

SECTION 7

SEDIMENT AND NUTRIENT LOSS ESTIMATES (RECOMMENDED APPROACH)

The preceding section has provided a review of concepts and methodology for estimating seasonal irrigation requirements, irrigation return flows from individual irrigated fields, and associated sediment, phosphorus and nitrogen losses. The purpose of this section is to bring together, in abbreviated form, the recommended procedure for estimating these parameters for a given irrigated field.

6-1/2"

IRRIGATION REQUIREMENTS AND RETURN FLOW ESTIMATES

The key to estimates of irrigation requirements and return flows from individual fields has been taken as the on-farm irrigation efficiency (E). Table 11 lists the irrigation efficiencies assumed in this study for various crops and irrigation systems of the Magic Valley area of Idaho. Adjustments may be dictated by existence of more precise data for a given locale or by a need to build internal consistency, a rooting-depth dependence of deep percolation losses, or similar considerations into a data set.

Once an appropriate set of base-level irrigation efficiencies has been assigned for selected crop, soil, and slope conditions, the percent runoff (R) plus percent deep percolation (P) is calculated from the relation

$$R + P = 100 - E.$$

In most cases, the R value for a given setting is the more easily measured (or estimated) of the two water loss figures. Base-level values of 25 percent and 35 percent, for example, were assigned to close-growing and row crops, respectively, in the Magic Valley area of southern Idaho. Once a value has been assigned, the percent deep percolation (P) can be simply calculated by difference. For sprinkler-irrigated fields, the P value can also be estimated as

$$P = 100 - E - W$$

where W represents percent wind and evaporative losses (assigned

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EPA-287 (Cin.)
(4-76)

a value of 10 percent in this study). A check on this figure, or an alternative calculation method, can be employed through use of the interrelationships in Table 15, if values for the coefficient of uniformity and the adequacy level are known or can be estimated for a given irrigation system-crop-soil combination. If, on the other hand, estimates of the uniformity coefficient and the percent deep percolation for a given sprinkler-irrigated setting are available, the adequacy level can be used as a qualitative check (via Table 15), assuming that the 50 percent, 75 percent, and 87.5 percent adequacy levels correspond to under-, adequately-, and over-irrigated conditions, respectively.

Modifications in the irrigation system or its management can next be introduced as adjustments to base-level irrigation efficiency values. Adjustments can be based upon reported efficiency values for the systems under consideration, anticipated changes in percent runoff and percent deep percolation, or similar considerations. As each adjustment in irrigation efficiency is adopted, corresponding revision of the percent runoff and percent deep percolation values is required as well. Such adjustments were described in considerable detail in the Section 6 subsection entitled "Furrow Irrigation Efficiency Estimates." They will not be repeated here.

Another useful parameter which can be derived from the concepts of Section 6 is the optimal frequency or number of irrigations. This can be calculated from the relation

$$F = Qc/D = Qc/(krw)$$

where F = the optimal number of irrigations (e.g., Table 9); Qc is the seasonal net irrigation requirement of the crop (e.g., Table 13); D = the depletable soil moisture (Table 8); k = a constant equal to 0.33 for potatoes and to 0.5 for other crops; r = the crop rooting depth; and w = the soil water-holding capacity. The problem with this approach is that relatively few Pacific Northwest irrigation practices are currently "optimal", so calculated F values may differ sustantially from actual numbers of irrigations. The concept is still useful for modeling or predictive purposes, however.

Finally, seasonal water application requirements (Qa values) for a given irrigated setting can be calculated from the relation

$$Qa = Qc/(E/100).$$

Quantities of individual-farm runoff (Ra) and deep percolation (Pa) return flow can then be calculated from the relations

$$Ra = Qa\ (R/100) \text{ and } Pa = Qa\ (P/100)$$

EPA-287 (Cin.)
(4-76)

TABLE 20. MULTIPLIERS TO THE BASE-LEVEL SEDIMENT LOSS VALUES TO ADJUST FOR SELECTED CROP TYPES

Crop type	Multiplier
Potatoes	1.0
Other row crops	0.4
Close-growing crops	0.05

Table 21 presents similar multipliers for various runoff values. These multipliers were derived by assuming that sediment loss varies as the square of the runoff value. For example, for a runoff of 15 percent, the proper multiplier would be

6-1/2"

$$(15\%/35\%)^2 = 0.18$$

as listed in the table. This relationship needs considerably more field testing and refinement. Gossett, for example, assumed annual sediment loss to be directly proportional to runoff volume. This is only one of many areas related to sediment

TABLE 21. MULTIPLIERS TO THE BASE-LEVEL SEDIMENT LOSS VALUES TO ADJUST FOR SELECTED RUNOFF VOLUMES

Runoff (%)	Multiplier
40	1.3
35	1.0
32.5	0.86
25	0.51
22.5	0.41
15	0.18
12.5	0.13
5	0.02

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

loss from irrigated croplands which requires considerably more research before exact relationships will be adequately defined.

In estimating sediment loss values where both crop type and runoff volumes vary, the appropriate crop-type multiplier is selected from Table 20 and the appropriate runoff multiplier is selected from Table 21 or calculated as (percent runoff/35 percent)^2. For a close-growing crop and an improved furrow system having only 22.5 percent runoff, for example, the seasonal sediment loss estimate would be

$$18(0.05)(22.5/35)^2 = 18(0.05)(0.41)$$

$$= 0.37 \text{ tons/acre } (0.83 \text{ mt/ha}).$$

As runoff volume declines for traditional furrow irrigation systems, stream size normally declines also, for length of set is determined more by sociological or institutional constraints. In cases where stream size and runoff volume might vary more or less independently, or where stream size variations might be known in lieu of runoff-volume variations, stream size variations can be assumed to produce sediment loss variations as [stream size(gpm)/8(gpm)]^2 or [stream size(l/sec)/0.5(l/sec)]^2.

The sediment loss estimates can be adjusted for other soil textures as well. Table 22 presents appropriate multipliers for other soil textures, as determined from universal soil loss equation (USLE) soil erodibility "K-factors." The multipliers tend to be about 15 percent higher than the relative values of Pfeiffer (1976), largely because a smaller K-factor has been assigned to silt loam soils. The other major difference between these values and Pfeiffer's concerns the relative erodibility of silty clay soils, with Pfeiffer's value nearly twice as large as those used for these studies. No reason for this discrepancy is readily apparent.

TABLE 22. MULTIPLIERS TO THE BASE-LEVEL SEDIMENT LOSS VALUES TO ADJUST FOR SELECTED SOIL TEXTURES

Soil texture	Multiplier
Silt loam	1.0
Loam	0.79
Sandy loam	0.53
Silty clay	0.34
Loamy sand	0.30

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

A change in soil texture may also imply a change in other factors related to sediment loss estimates. For instance, the runoff volume, the stream size, and even the length of set may be varied from one soil type to the next. In general, if percent runoff is assumed to remain constant, stream size must increase as more coarse-textured soils are irrigated, since the infiltration rate increases. This may well be one case where stream size and runoff volume vary independently, and should be independently adjusted. With the present uncertainty in runoff volume and soil texture multipliers, however, such sophistication of estimates appears unwarranted.

Adjustments in sediment loss estimates should also be made to reflect the effects of field slope. The multipliers of Table 23 are provided for this purpose. These multipliers were derived by assuming a squared dependence of erosional losses on field slope. They were calculated as the ratio (field slope/1.5 percent)^2. For example, the multiplier required for a slope of 2.5 percent is

$$(2.5 \text{ percent}/1.5 \text{ percent})^2 = 2.78$$

as shown in the table.

As with a change in soil texture, a change in field slope also implies changes in various management-related factors. Even though stream size is normally reduced for steeper slopes, runoff percent will often increase, since proper management becomes more difficult as field slope increases. Growers tend to use a stream

TABLE 23. MULTIPLIERS TO THE BASE-LEVEL SEDIMENT LOSS VALUES TO ADJUST FOR SELECTED FIELD SLOPES

Slope (%)	Multiplier
0.25	0.03
0.50	0.11
1.00	0.44
1.5	1.00
2.5	2.78
3.5	5.40
5.0	11.00
8.0	28.00

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EPA-287 (Cin.)
(4-76)

size that is too large in such situations. In addition, the stream on steeper slopes has greater kinetic energy, and tends to maintain suspended solids in suspension rather than depositing them at mid-field. Length of set is also assumed to remain constant, even though the stream may reach the tail of the field more rapidly as slope increases, because of the primary dependence of set length on sociological and institutional contraints.

A simultaneous change in soil texture and in slope can be dealt with by multiplying the base-level sediment loss value by the appropriate multipliers. Suppose, for example, that it is desired to adjust sediment loss for potatoes from the seasonal base-level sediment loss value of 18 t/acre (40 mt/ha) on silt loam soils of 1.5 percent slope to sandy loam soils of 2.5 percent slope. From Tables 22 and 23, the required multipliers would be 0.53 and 2.78. Hence, the adjusted seasonal sediment loss estimate would be

$$(18)(0.53)(2.78) = 26.5 \text{ t/acre } (59.4 \text{ mt/ha}).$$

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If the increase in slope had been for a silt loam soil instead, the corresponding seasonal sediment loss estimate would be

$$(18)(2.78) = 50.0 \text{ t/acre } (112 \text{ mt/ha}).$$

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As many of the irrigated soils which have been studied recently in southern Idaho are of silt loam type, this example dramatizes the importance of accurately specifying all possible conditions when trying to extrapolate sediment loss estimates from one study site to another.

Once sediment loss estimates have been generated, estimates of associated total-phosphorus loss (lb/acre or kg/ha) are calculated by multiplying the sediment loss estimate (t/acre or mt/ha) by 2.8 or 1.4, respectively. For the base-level conditions, for example, the appropriate seasonal total-phosphorus loss estimates would be

$$18 \times 2.8 = 50.4 \text{ lbs phosphorus/acre } (56.5 \text{ kg phosphorus/ha}).$$

NITROGEN LOSS ESTIMATES

For estimating nitrogen loss, a slightly-modified form of Pfeiffer's (1976) equation has been employed,

$$N_L = 0.072\ (N_f)^{1.05}(Q_d)^{0.7}$$

where N_L = nitrogen leached (lb/acre/season); N_f = nitrogen applied (lb/acre/season); and Q_d = amount of drainage water (in/season). The metric equivalent expression merely substitutes a constant of 0.038 instead of 0.072, if values are expressed in

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EPA-287 (Cin.)
(4-76)

kg/ha/season and cm/season. Values of N_f are obtained from records of growers or fertilizer companies, or from fertilizer guides for various crop-soil combinations. Values of Q_d (equivalent to Pa in Section 6) are calculated as described at the beginning of this section.

The above equation describes nitrate leaching values for southern California croplands (i.e., the data base from which the equation was developed) with considerable accuracy. It tends to over-estimate Pacific Northwest nitrogen-loss values by two- to to three-fold, however. To correct for this, two modifications have been introduced:

1. Each irrigated field has been conceptually divided into ten uniform increments, with Pfeiffer's equation applied to each increment independently. Leaching values for each tenth-field increment are then summed to give a field-wide nitrogen loss value. In this manner, the most heavily leached portions of the field (e.g., beneath the furrows in furrow-irrigated settings) can contribute no further nitrogen once all of their nitrogen has been leached, no matter how much additional water percolates. Furthermore, furrow-irrigated fields can be simulated by "placing" less nitrogen initially in the most heavily leached increment(s). Such an approach was used as part of a simplified model for simulated-furrow leaching in Section 6. Other models could be adopted as well. Calculations of field-subunit leaching for various uniformity coefficients and adequacy levels are provided in Table 16, assuming normally-distributed water application. Corresponding field-wide leaching estimates are given in Table 16.

2. A set of denitrification multipliers have been introduced, to correct for gaseous loss of unutilized nitrogen instead of leaching losses. These multipliers are applied to field-wide or field-increment nitrate-leaching estimates, in a manner similar to the application of sediment-loss multipliers earlier in this section. A set of denitrification multipliers, keyed to soil texture or to saturated soil hydraulic conductivity, is given in Table 19.

ECONOMIC ESTIMATES

The remainder of this report demonstrates application of the recommended methodology in solving problems of pollution from irrigation return flows in specific areas of the Pacific Northwest. Each problem area should be approached as a unique set of physical, economic, and environmental characteristics. Specific physical and economic data should be collected and analyzed for each such area prior to implementation of abatement programs. Appropriate data for two Pacific Northwest study areas (the Magic Valley area of southern Idaho and the Umatilla

EPA-287 (Cin.)
(4-76)

area of northcentral Oregon) are presented in Section 6 and in Appendix A. Results of such analyses, along with results from similar analyses for the Yakima Valley of southcentral Washington, will be presented in Section 8.

Other approaches could be used to assess the cost and effectiveness of abatement control practices. Most would require data inputs similar to those specified, however. For the economic appraisals, the involvement of competent economists is desirable to assist in properly constructing and analyzing the economic data and in relating them to the physical and environmental world.

Linear programming was used extensively as a tool in the studies reported herein. This is a useful technique for considering managerial problems involving choices among alternative processes (pollution abatement practices). Linear programming allows the selection of economically optimal combinations of crops and irrigation management practices, subject to any environmental constraints which may be imposed on a farm or river basin. The combination of activities selected by this technique will be that which maximizes returns or minimizes costs, depending upon what the stated objectives and constraints may be. While it is not absolutely necessary to use linear programming techniques, such an approach provides information that may be obtained only with considerable difficulty in other ways. If such techniques are employed, it is desirable to obtain the assistance of someone experienced in their application.

Whether linear programming is used or not, it will generally be necessary to collect economic data similar to those provided in Appendix A. These tables also provide an example of how such data can be organized and used. Sources of economic data are varied, making it desirable to obtain competent economic assistance prior to their collection and/or application.

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SECTION 8

CASE STUDIES FOR SELECTED PACIFIC NORTHWEST AREAS

The Magic Valley of southern Idaho and the Umatilla region of northcentral Oregon have been specifically chosen for this study to demonstrate how one might use the data from preceding sections to estimate cost and effectiveness of selected pollution abatement practices. Linear programming techniques have been used to analyze typical irrigated farms in each area. Representative farm models included current cropping patterns and irrigation systems, as well as potential control practices for abating pollution from irrigation return flows. A brief description of each farm model follows.

The Magic Valley consists of Jerome and Twin Falls counties of southcentral Idaho. The irrigated acreage in this study area is about 390,000 acres (158,000 ha). Soils are generally silt loams and sandy loams, with terrain ranging from level to gently rolling. Water is diverted from the Snake River and delivered to the farms through unlined channels. Furrow irrigation is predominant, accounting for about three-fourths of all irrigated acreage. Most lands are irrigated with siphon tubes, though the use of gated-pipe is increasing. Irrigation efficiency in the area is low, averaging less than 40 percent.

The Umatilla area lies in Morrow and Umatilla counties of northcentral Oregon, adjacent to the Columbia River. The soils are sandy and the terrain level to gently rolling. Total irrigated acreage in this area is about 75,000 acres (30,000 ha). All of this land is assumed to be irrigated with center-pivot irrigation, eliminating field runoff and sediment loss problems. Farms are large, ranging from 500 to over 10,000 acres (200 to 4,000 ha).

Economic assessment of pollution abatement practices is obviously dependent upon the physical and economic data used for the analysis. The tables of Appendix A show the major physical and economic input data used for the Magic Valley and Umatilla area model farms. For further details on either the economic or physical characteristics of these areas, the reader is referred to Obersinner (1979).

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

MAGIC VALLEY AREA

Overview

Table 24 shows the soil textures and slopes assumed for three Magic Valley model farms. Each farm is assumed to contain 300 acres (122 ha) of cropland. Cropping patterns used in the analysis are presented in Table 25. Cropping Pattern 1 is the benchmark situation. The remaining cropping patterns are used to assess their effectiveness in reducing sediment and fertilizer losses. Cropping Patterns 2 and 3 primarily represent a

TABLE 24. SOIL TEXTURES AND SLOPES OF THE MAGIC VALLEY MODEL FARMS

Model Farm	Texture	Slope (%)
Farm 1	silt loam	1.5
Farm 2	silt loam	2.5
Farm 3	sandy loam	1.5

TABLE 25. CROPPING PATTERNS DEFINED FOR MAGIC VALLEY MODEL FARM 1

	Cropping pattern		
Crop	1	2	3
		(acres) a/	
Alfalfa	80	80	100
Spring wheat	80	60	100
Peas	0	40	0
Field corn	0	0	0
Dry beans	60	120	60
Potatoes	80	0	40

a/ 1 acre = 0.405 hectare.

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EPA-287 (Cin.)
(4-76)

substitution of other crops for potatoes, a crop associated with relatively large water, phosphorus, and fertilizer nitrogen usage. Throughout this section there is reference to control practices considered for pollution abatement. Table 26 provides a listing of irrigation systems considered as control practices in this section. Abbreviations of these irrigation systems are identified in Table 10. Associated cropping patterns (Table 25) are identified by the number appended to each abbreviation. For example, PFRW-1 would refer to a present furrow irrigation system in the Magic Valley area of Idaho (Table 10) using Cropping Pattern 1 (Table 25). Estimated efficiencies for major crops and alternative irrigation systems in the Magic Valley area are provided in Table 11. Corresponding runoff and deep percolation values are given in Tables 12 and A-1, with deep percolation values for the Umatilla area of Oregon given in Table A-2. Seasonal net irrigation and water application requirements for the two study areas are given in Table 13 and in Tables A-3 and A-4, with phosphorus and nitrogen fertilization estimates given in Table A-5 and A-6, and with sediment and nitrogen loss estimates for the Magic Valley given in Tables A-7 and A-8. Economic values for the various irrigation systems assumed for the two study areas are given in Tables A-9 to A-22.

Model Farm 1

Table 26 presents results of employing selected control practices on Model Farm 1. Quantities of capital investment, input use, runoff and deep percolation losses are given for each model solution.

Benchmark (BMRK)

Column 1 of Table 26 presents model results for the benchmark farm (BMRK). These results are used as a base of comparison for all subsequent solutions. The benchmark is assumed to be a typical furrow-irrigated farm in the Magic Valley, growing dry beans, potatoes, spring wheat and alfalfa hay (Cropping Pattern 1, Table 25). Water losses, in the form of runoff and deep percolation, act as the medium of transport for sediment and nitrogen, respectively. Phosphorus is lost primarily through its attachment to sediment. For the benchmark farm, 5,534 acre-in (5,693 ha-cm) of runoff would transport 1,972 tons (1,789 mt) of sediment and 5,522 lbs (2,507 kg) of phosphorus from the farm. Deep percolation water losses of 4,750 acre-in (4,886 ha-cm) would transport 5,292 lbs (2,403 kg) of nitrogen beyond the root zones of crops grown on the farm.

Input use by the farm is also shown in Table 26. Annual water use would be 18,280 acre-in (18,805 ha-cm), implying that slightly more than one-half of the applied water would be lost through runoff and deep percolation. On-farm pumping would not be required for the furrow irrigation system, so energy utili-

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EPA-287 (Cin.)
(4-76)

TABLE 26. NET RETURNS, WATER AND POLLUTANT LOSSES, AND INPUT USE FOR THE IRRIGATION SYSTEM CHANGES AND SEDIMENT RETENTION DEVICES USED ON MAGIC VALLEY FARM 1

		Irrigation system changes[a]							Sediment retention devices[b]	
Item	Unit	BMRK[c]	IFRW-1	CTBK-1	PMPBK-1	GPIPE-1	MLTST-1	SDRL-1	SPND-1	FSTRP-1
Net returns	$	67,453	66,514	63,797	63,815	63,418	59,512	56,742	64,932	67,081
Cost	$	---	939	3,656	3,652	4,035	16,941	10,711	2,521	372
Reduction in net returns	%	---	1.4	5.4	5.4	6.0	25.1	15.9	3.7	0.6
Capital investment[d]	$	---	0	0	10,821	53,844	170,790	88,635	0	0
Losses:										
Runoff	ac-in[e]	5,534	4,494	2,698	0	2,178	472	0	5,530	5,518
Deep percolation	ac-in	4,750	3,796	2,780	4,750	2,252	932	2,664	4,746	4,736
Sediment	tons	1,972	1,694	984	0	790	44	0	592	1,663
Phosphorus	lbs	5,522	4,743	2,755	0	2,212	124	0	1,656	4,655
Nitrogen	lbs	5,292	4,146	3,304	5,292	2,864	1,494	3,988	5,288	5,282
Reduction in losses:										
Sediment	tons	---	278	988	1,972	1,182	1,928	1,972	1,380	309
Phosphorus	lbs	---	779	2,767	5,522	3,310	5,398	5,522	3,866	867
Nitrogen	lbs	---	1,146	1,988	0	2,428	3,798	1,304	4	10
Percent reduction in losses:										
Sediment & phosphorus	%	---	14.1	50.0	100.0	59.9	97.8	100.0	70.0	15.7
Nitrogen	%	---	21.7	37.6	0	45.9	71.8	24.6	0.1	0.2
Input use:										
Water	ac-in	18,280	16,260	13,480	12,746	12,500	9,360	11,840	18,266	18,185
Energy	KWH	0	0	0	50,116	0	1,030	355,338	0	0
Labor	hrs	1,140	1,140	2,280	1,140	40	46	456	1,139	1,135
Nitrogen fert.	lbs	27,620	26,440	25,660	27,620	25,180	23,920	26,500	27,590	27,540
Phosphorus	lbs	9,500	9,500	9,500	9,500	9,500	9,500	9,500	9,493	9,467

[a] Each of these model solutions includes cropping pattern 1.

[b] Using the present furrow irrigation system.

[c] Terms defined in Table 10, except for SPND = sediment pond, and FSTRP = filter strip.

[d] Additional capital investment for irrigation systems.

[e] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.; 1 ton = 0.908 metric ton; 1 pound = 0.454 kg.

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zation for this purpose would be zero. The seasonal labor requirement for operating the irrigation system would be 1,140 hours. Nitrogen fertilizer application to the farm would be 27,620 lbs (12,539 kg), with a phosphorus fertilizer application of 9,500 lbs (4,313 kg).

Net returns to land, management and overhead would be $67,453. Crop prices represent an average for the years 1975 to 1977, while crop production costs and input prices represent those prevailing in early 1978. This net income figure is used subsequently for calculating net income losses due to pollution abatement practices.

Irrigation System Changes

Improved Furrow System (IFRW-1)--

For the improved furrow system, a higher level of management is assumed than for the present furrow system, in order to regulate stream size and minimize runoff and deep percolation losses. The length of set is assumed just adequate to replenish depleted soil moisture. Finally, irrigations are assumed to be scheduled according to crop water needs, with the assistance of an irrigation scheduling service. The added costs associated with this system are shown in Table A-10.

Use of the IFRW-1 system would reduce runoff and deep percolation losses by about 1,000 acre-in (1,030 ha-cm) each. The reduction in runoff would decrease sediment and phosphorus losses by about 15 percent. Sediment loss would be reduced by 280 tons (254 mt), but phosphorus loss would be reduced by only 780 lbs (354 kg). Nitrogen losses would decline by 22 percent, or about 1,150 lbs (522 kg).

Although water losses would decline, energy still would not be required for pumping water under the improved furrow system. The quantities of irrigation labor and phosphorus fertilizer inputs have been assumed equivalent to those of the benchmark. Since phosphorus losses decline, phosphorus fertilizer needs should also decline. Such a refinement was not considered for this study, however.

Cut-Back Furrow System (CTBK-1)--

For the cut-back furrow system, additional labor is assumed input to the present furrow system to reduce stream size once the stream has reached the end of a given furrow. As shown in Table 26, this technique would reduce runoff losses by 2,800 acre-in (2,880 ha-cm), resulting in a 50 percent reduction in sediment and phosphorus losses as compared to the benchmark solution. Sediment losses would be reduced by nearly 1,000 tons (907 mt), with phosphorus losses being reduced by 2,800 lbs (1,271 kg). Deep percolation losses of nitrogen would be reduced by 2,000 lbs (900 kg), or approximately 40 percent.

EPA-287 (Cin.)
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Water usage would decline by 4,800 in (4,900 ha-cm) when using this system, and the decreased nitrogen losses would allow application of about 2,000 lbs (900 kg) less nitrogen. Farm net returns would go down about $3,700, or about 5 percent, reflecting the cost of additional labor minus the savings in nitrogen fertilizer. These results suggest that substantial pollution abatement could be achieved at reasonably small costs by imposing better irrigation management.

Pump-Back Furrow System (PMPBK-1)--

The pump-back furrow system, using management levels equivalent to those of the present-furrow system, involves collecting field runoff in a pond and pumping it back to a head ditch for reuse. The collection pond doubles as a sediment pond, and retained sediment is spread back onto nearby fields. Runoff, sediment and phosphorus losses from the farm would be essentially eliminated (Table 26). Deep percolation losses would remain unchanged, leaving nitrogen usage and nitrogen losses equivalent to those of the benchmark.

By eliminating runoff losses, water applied to the field would decline by about 5,500 acre-in (5,600 ha-cm). The energy required for pumping back the runoff would be about 50,000 kilowatt hours (KWH). Because the pump system is assumed to be automatic, and sediment spreading costs have been assigned separately, labor required for operating this system should remain unchanged from that of the benchmark.

Use of the pump-back would reduce net returns by about $3,600, or 5 percent. This figure reflects additional energy costs, and $2,521 annual costs for excavating and spreading sediment from the sediment pond, as well as the opportunity cost of cropland taken out of production by the pond (0.5 acre, or 0.2 ha). The capital investment required would be $10,820 ($36 per acre, or $89 per ha).

Gated-Pipe System (GPIPE-1)--

The automatic gated-pipe system features a mechanism to automatically reduce stream size after the stream reaches the furrow end (such as initially irrigating successive halves of the field with a normal stream, and then the entire field with a stream size only one-half as large), plus the improved management practices associated with the improved-furrow system. As a result, runoff and deep percolation losses would be substantially reduced. Table 26 shows that runoff losses would decline 3,300 acre-in (3,400 ha-cm) and deep percolation losses about 2,500 acre-in (2,570 ha-cm). This would reduce sediment and phosphorus losses by about 60 percent and nitrogen losses by about 45 percent compared to the benchmark condition.

The gated-pipe system would not require energy for pumping water, and the labor requirement would be only about 5 percent of

EPA-287 (Cin.)
(4-76)

that required for the present furrow system. Net farm returns would be reduced by $4,000, or 6 percent. The additional annual cost of the gated-pipe system would be offset, in part, by lower expenditures on irrigation labor and nitrogen fertilizer. The additional cost could be largely attributed to the increased capital investment in the system (see Table A-16).

Multi-Set System (MLTST-1)--

The multi-set system divides the field into several subsections, using underground lateral pipes to shorten the length of run. It also imposes the improved management associated with the improved-furrow system. The multi-set system would reduce runoff by approximately 90 percent, or about 5,000 acre-in (5,100 ha-cm). This would produce reductions of about 98 percent in sediment and phosphorus losses. Deep percolation losses would be decreased about 80 percent, reducing nitrogen losses approximately 70 percent. Water application would decline about 9,000 acre-in (9,300 ha-cm), to about 50 percent of the benchmark requirement. Despite the reduced overall water requirements, water must be applied to all laterals concurrently when using this system, so the multi-set system requires a peak water volume slightly greater than that normally delivered to fields by the present-furrow system. Hence, water must be stored in a pond to be pumped at peak requirement periods. About 1,000 KWH of energy would be required for pumping this water. Only a small quantity of irrigation labor would be required to operate the multi-set system, since it is fully automatic. Nitrogen fertilizer use by the farm should decline by 3,700 lbs (1,700 kg).

Investment in the multi-set system would reduce annual net returns by $17,000. Most of the cost associated with this system could be attributed to annual ownership costs ($15,000 for depreciation and interest) associated with the capital investment requirement of $569 per acre ($1,405 per ha; see Table A-17). The annual cost of the multi-set system would be partially offset by savings in labor and nitrogen fertilizer.

Side-Roll Sprinkler System (SDRL-1)--

The side-roll sprinkler system includes the improved water management practices associated with the improved-furrow system. Table 26 shows that runoff, sediment and phosphorus losses would be essentially eliminated by conversion to a side-roll sprinkler system. Deep percolation losses would also decline with this system, due to improved management and increased uniformity of water application. Deep percolation losses would decline by about 2,100 acre-in (2,160 ha-cm), reducing nitrogen losses about 25 percent.

Sprinkler systems require on-farm pressurization, and the side-roll system would use about 355 megawatt hours (MWH) of energy for this purpose. The side-roll system is semi-automatic,

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so the irrigation labor requirement would be less than one-half that of the benchmark. The lower quantities of deep percolation and nitrogen loss would require 1,000 lbs (450 kg) less nitrogen fertilizer.

Conversion to the side-roll sprinkler system would reduce farm net returns about $11,000, or 16 percent. Reduced expenditures on labor and nitrogen fertilizer would partially offset the annual cost of $37 per acre ($91 per ha; see Table A-18). It was assumed that head and tail ditches required by the furrow system would be removed to accommodate the sprinkler system. Cropland gained as a result was assumed to offset that taken out of production by the irrigation pond required for this system. Hence, the annual cost of this system does not include an opportunity cost for foregone crop production.

Sediment Retention Devices

Sediment Pond (SPND-1)--

For this control practice, a single large sediment pond was assumed which retains 70 percent of the sediment lost from fields. Runoff, deep percolation, nitrogen loss, and input use would be essentially unchanged by this practice. Sediment and phosphorus losses would be reduced by 1,400 tons (1,300 mt) and 3,900 lbs (1,800 kg), respectively (Table 26).

Use of the sediment pond would result in a reduction in net farm returns of about $2,500, or 4 percent. This cost includes the annual expenditure for excavating and spreading sediment retained in the pond, as well as net returns foregone as a result of the loss of one-third acre (0.8 ha) of cropland to the pond.

The use of a single sediment pond for a 300-acre (122-ha) farm presumes that a single drain accounts for all surface irrigation return flows leaving the farm. It is possible that farm terrain would not accommodate the use of a single sediment pond. In this case, additional sediment ponds could change the costs of this control practice from those shown here. Since all cost calculations were proportioned to pond size and amount of retained sediment, such costs would not be expected to change substantially with the need for smaller sediment ponds. Sediment retention devices do not in general prevent loss of productivity through continued erosion, particularly from the head of the field where stream size is greatest.

Filter Strips (FSTRP-1)--

Filter strips were assumed to be located at the bottom of all fields except those cropped to potatoes or alfalfa. Filter strips would not be generally feasible on highly erosive crops like potatoes, since they would not function after the first irrigation. The use of filter strips is redundant on alfalfa, since the crop is already close-growing and an effective filter

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of suspended sediments. Filter strips were assumed to reduce sediment loss from other fields by 50 percent. Runoff, deep percolation and nitrogen losses were not assumed to be reduced by the strips. Sediment and phosphorus losses would be reduced by 300 tons (270 mt) and 900 lbs (410 kg), respectively. Compared to the sediment pond, filter strips would be relatively ineffective. They have been assumed to retain only 50 percent, rather than 70 percent, of the sediment lost from the fields of the farm. Furthermore, potatoes are assumed to produce much of the sediment lost from the farm.

Input use by the farm would remain essentially unchanged. The use of filter strips would reduce net returns by $372, or 0.6 percent. This cost would include the annual cost of seeding the filter strips and spreading the retained sediment onto adjacent fields (Table A-19). Also included are the net returns foregone as a result of the loss of cropland to the filter strips. Capital investment would not be required for this control practice.

Cropping Pattern Changes

Although cropping pattern changes would be effective in reducing sediment and nutrient losses from the model farm, reductions in net returns would be relatively large when compared to those from irrigation system changes or the use of sediment retention devices. Results of optional cropping patterns are shown in Table 27.

Cropping Pattern 2 (PFRW-2)--

Cropping Pattern 2 (Table 25) represents a substitution of peas and dry beans for potatoes and wheat. This cropping pattern is common in the Magic Valley. Runoff would decline about 1,000 acre-in (1,030 ha-cm) from the benchmark, reducing sediment and phosphorus losses by about 50 percent each (Table 27). The reduction in runoff and the substantial reduction in sediment and phosphorus losses would be due to the elimination of potatoes, a crop associated with large quantities of such losses. Deep percolation losses would also decline by about 1,000 acre-in (1,030 ha-cm), with nitrogen losses being reduced by about 75 percent. Net returns would be only about two-thirds those of the benchmark, however, again due to the elimination of potatoes from the cropping pattern.

Cropping Pattern 3 (PFRW-3)--

Cropping Pattern 3 represents a substitution of wheat and alfalfa for one-half of the potatoes (Table 25). Runoff and deep percolation losses would each be reduced nearly 600 acre-in (620 ha-cm) from those of the benchmark farm (Table 27). The reductions in sediment, phosphorus and nitrogen losses would be only about two-thirds of those associated with Cropping Pattern 2. Pollutants would generally be changed in proportion to

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EPA-287 (Cin.)
(4-76)

TABLE 27. NET RETURNS, WATER AND POLLUTANT LOSSES, AND INPUT USE FOR CROPPING PATTERN CHANGES, AND COMBINATION IRRIGATION SYSTEM AND CROPPING PATTERN CHANGES, FOR MAGIC VALLEY FARM 1

			Cropping pattern changes		Combination irrigation system & cropping pattern changes	
Item	Unit	BMRK	PFRW-2	PFRW-3	CTBK-2	GPIPE-2
Net returns	$	67,453	44,742	53,589	41,866	39,674
Cost	$	---	22,711	13,864	25,587	2,779
Reduction in net returns	%	---	33.7	20.6	37.9	41.2
Capital investment[a/]	$	---	0	0	0	53,844
Losses:						
Runoff	ac-in[b/]	5,534	4,548	4,954	2,218	1,788
Deep percolation	ac-in	4,750	3,720	4,154	2,188	1,752
Sediment	tons	1,972	1,002	1,304	486	384
Phosphorus	lbs	5,522	2,806	3,651	1,361	1,075
Nitrogen	lbs	5,292	1,384	3,504	896	802
Reduction in losses:						
Sediment	tons	---	970	668	1,486	1,588
Phosphorus	lbs	---	2,716	1,871	4,161	4,447
Nitrogen	lbs	---	3,908	1,788	4,396	4,490
Percent reduction in losses:						
Sediment & phosphorus	%	---	49.2	33.9	75.4	80.5
Nitrogen	%	---	73.8	33.8	83.1	84.8

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EPA-287 (Cin.)
(4-76)

TABLE 27. CONTINUED

Item	Unit	Cropping pattern changes			Combination irrigation system & cropping pattern changes	
		BMRK	PFRW-2	PFRW-3	CTBK-2	GPIPE-2
Input use:						
Water	ac-in	18,280	15,600	17,240	11,720	10,920
Energy	KWH	0	0	0	0	0
Labor	hrs	1,140	850	990	1,700	34
Nitrogen fertilizer	lbs	27,620	11,220	20,800	10,640	10,540
Phosphorus	lbs	9,500	6,120	7,660	6,120	6,120
Cropping pattern		1	2	3	2	2

[a] Additional capital investment for irrigation systems.

[b] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.; 1 ton = 0.908 metric ton; 1 pound = 0.454 kg.

PAGE NUMBER

EPA-287 (Cin.)
(4-76)

the shift in potato acreage.

Although input use associated with Cropping Pattern 3 would be less than that for the benchmark cropping pattern, it would still be greater than that for Cropping Pattern 2. Net returns would be reduced about 20 percent from those of the benchmark, again in response to the shift from potatoes.

Combination Irrigation System and Cropping Pattern Changes

In some cases it might be more appropriate to combine two or more of the control practices described above. Using filter strips on one part of a farm while using a sediment pond on another (more erosive) portion, for example, might be a reasonable plan. Similarly, it might be possible to superimpose an irrigation management service upon part or all of a farm in combination with one or more irrigation systems or sediment retention devices. The number of such potential combinations is so large that it was beyond the scope of this study to explore such avenues. The reader should appreciate the opportunities and needs for a combined approach to pollution abatement, however.

A Comparison of Control Practices

Figure 7 illustrates the costs of control practices and their associated sediment losses for Farm 1. The least-cost method of reducing sediment losses from about 2,000 tons (1,800 mt) to 1,600 tons (1,450 mt) would be the use of filter strips (FSTRP-1) on all fields except potatoes and alfalfa (where this approach is not deemed applicable). The resulting cost to the farm would be about $400, or $1.18 per ton ($1.30 per mt) of sediment abatement. An on-farm sediment pond (SPND-1) would reduce sediment losses to about 600 tons (540 mt) at a cost of $2,500, or $1.79 per ton ($1.97 per mt) of retained sediment.

Complete elimination of sediment losses could be accomplished by reducing field runoff with a pump-back system (PMBK-1) at a minimum cost of about $3,600. The average cost of this system would be about the same as for the sediment pond, or $1.85 per ton ($2.04 per mt) of sediment retained.

Connecting the points corresponding to the cost-sediment loss levels of these three control practices results in what can be termed an "efficiency frontier." Such a frontier is merely a line connecting those practices shown to be most efficient for achieving any level of pollution abatement. Those practices lying above this line will cost more to achieve the same level of abatement. It is likely that a combination of two or more control practices used on different portions of the farm would result in costs not on the curve of Figure 7. For example, reducing sediment losses from 1,600 tons (1,450 mt) to 600 tons

(540 mt) might be accomplished most efficiently by using filter strips on some fields and sediment ponds on others. The average costs of each control practice were estimated in this study, however, only for the situation where each was used on the entire farm. Using a given control practice on only a part of the farm might cause the average cost to vary, depending on the control practice under consideration. Adjustments in the size of sediment retention devices could probably be achieved at relatively constant average cost. Changing the size and the number of pumps and pipelines of a pump-back system could not likely be accomplished without affecting the average cost, however.

The effectiveness of each control practice is also a function of the crop being grown, among other factors. Similarly, a pump-back system might be used on a smaller scale to efficiently achieve the same abatement levels as sediment ponds or filter strips without substantially changing the average costs indicated by Figure 7. For the same reason, a smaller sediment pond might be used to efficiently reduce sediment loss to the levels corresponding to the use of filter strips.

All control practices lying above the efficiency frontier would cost more to reduce sediment losses than those actually on the frontier. Use of the cut-back (CTBK-1) or gated-pipe (GPIPE-1) systems, for example, would be several thousand dollars more costly to the grower than the use of sediment ponds or pump-back systems in achieving roughly comparable reductions in sediment losses. This is due to the relatively large labor requirements of the cut-back system and to the capital investment requirement of the gated-pipe system. Conversion to a different cropping system (e.g., PFRW-2) would be a much more expensive control measure.

Converting to capital-intensive irrigation systems would be an effective, but costly, alternative for reducing sediment losses. Net returns would be reduced by $11,000 with the side-roll irrigation system (SDRL-1) and by $17,000 with the multiset irrigation system (MLTST-1), while achieving virtually the same abatement level as a pump-back system. The pump-back system does not reduce nitrogen losses, however, while the other two do. Therefore, a control practice may still be chosen because it is efficient in abating more than one pollutant, and not just because it is most efficient in controlling a single pollutant.

As indicated above, control practices requiring cropping pattern changes are relatively inefficient in reducing sediment loss. Net returns would be reduced by $23,000 and $14,000 for changes to Cropping Patterns 2 and 3 (PFRW-2, PFRW-3), respectively, while sediment losses would be reduced only to about half the benchmark (BMRK) level. A cropping pattern change

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(4-76)

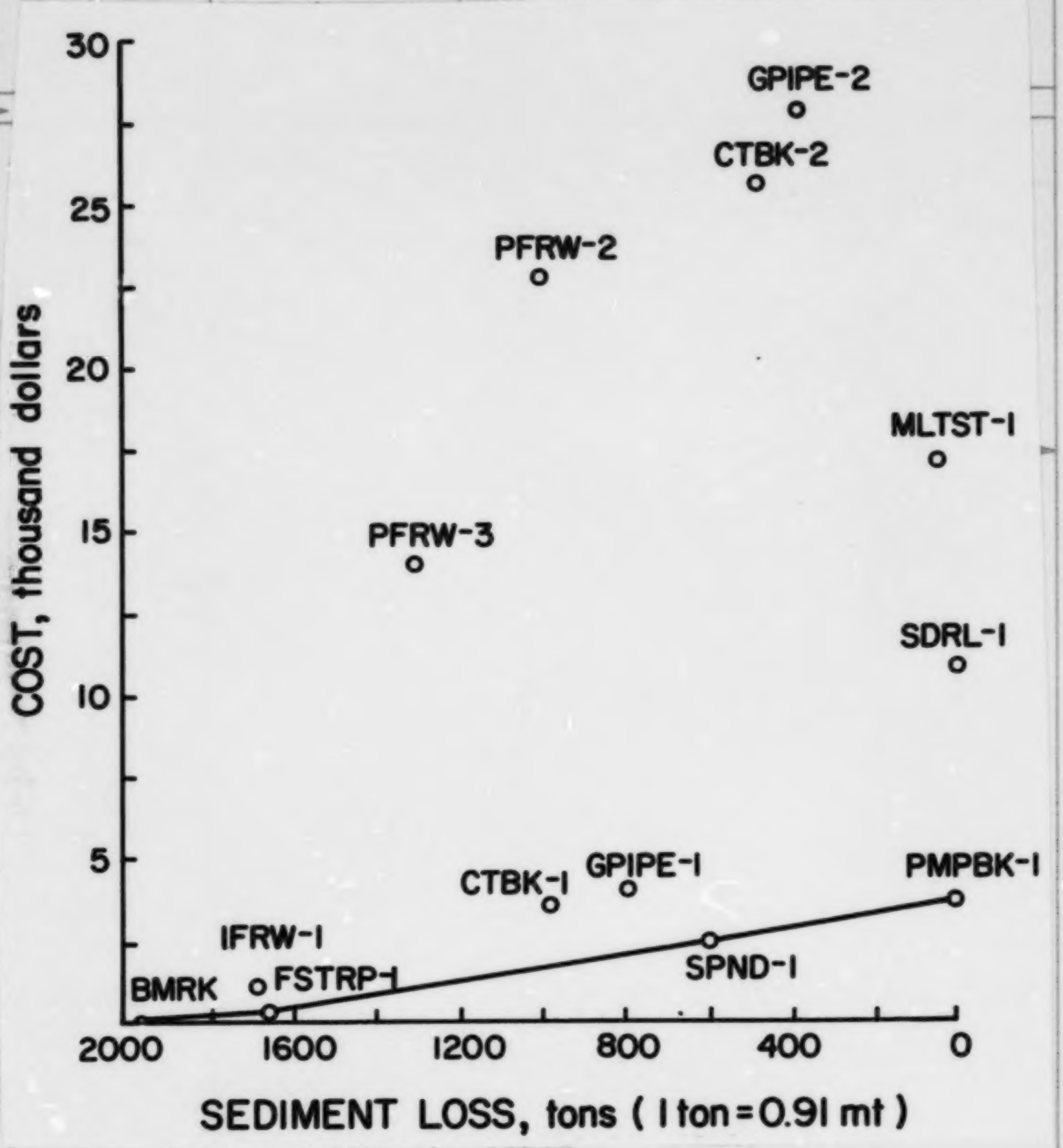

Figure 7. On-farm costs of reducing sediment loss using alternative control practices on Magic Valley Farm 1.

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EPA-287 (Cin.)
(4-76)

combined with conversion to an alternative irrigation system might be more effective in reducing sediment loss than a change in cropping pattern alone, but also more costly to the grower. The cut-back system with Cropping Pattern 2 (CTBK-2), for example, would reduce sediment losses by about 75 percent, but cost the grower $26,000. The gated-pipe system combined with the same cropping pattern (GPIPE-2) would reduce sediment losses by 80 percent and cost the grower $28,000.

Phosphorus loss was assumed to be directly proportional to sediment loss in this study, at 2.8 lbs per ton (1.4 kg per mt) of sediment. Hence, the relative cost-effectiveness of the control practices shown in Figure 7 for reducing sediment loss also applies to reductions in phosphorus loss. The assumed constancy of the sediment:phosphorus ratio is overly simplistic, however. Future research should provide information allowing refinement of phosphorus loss estimates.

Nitrogen Losses--

Figure 8 illustrates the cost and effectiveness of selected control practices for reducing nitrogen losses in the Magic Valley area of Idaho. The least-cost method of reducing nitrogen losses from the benchmark level of 5,300 lbs (2,410 kg) to a level of 4,100 lbs (1,860 kg) would be to use improved irrigation management practices (IFRW-1). The cost to the farm would be about $900, or $.75 per lb ($1.65 per kg) of nitrogen-loss abatement. Reducing losses of nitrogen to 2,900 lbs (1,300 kg) would be most efficiently accomplished by investment in a gated-pipe system (GPIPE-1), at a cost of $4,000, or $1.67 per lb ($3.68 per kg) of nitrogen-loss abatement. Reducing losses to 1,500 lbs (681 kg) in a least-cost manner would require conversion to the capital-intensive multi-set system (MLTST-1), at a cost of $4.74 per lb ($10.44 per kg) of nitrogen-loss abatement. Reductions in nitrogen losses below 1,500 lbs (680 kg) would require changes in cropping pattern, as well as the adoption of another irrigation system, costing the grower more than $25,000. The cut-back system combined with Cropping Pattern 2 (CTBK-2), for example, would reduce losses to 900 lbs (410 kg) at a cost of $26,000. Use of a gated-pipe system combined with the same cropping pattern (GPIPE-2) would reduce losses to 800 lbs (360 kg) at a cost of $28,000, representing an average cost of $6.22 per lb ($13.70 per kg) of nitrogen-loss abatement. These latter, more expensive control practices also would be effective in reducing sediment losses, however, and hence might be chosen for such reasons.

Reducing nitrogen fertilizer losses to levels between those corresponding to specific control practices on the efficiency frontier would require a combination of control practices. If the control practices involve a change in irrigation system or cropping pattern, this can be interpreted as a conversion of part of the farm to a second irrigation system or cropping

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(4-76)

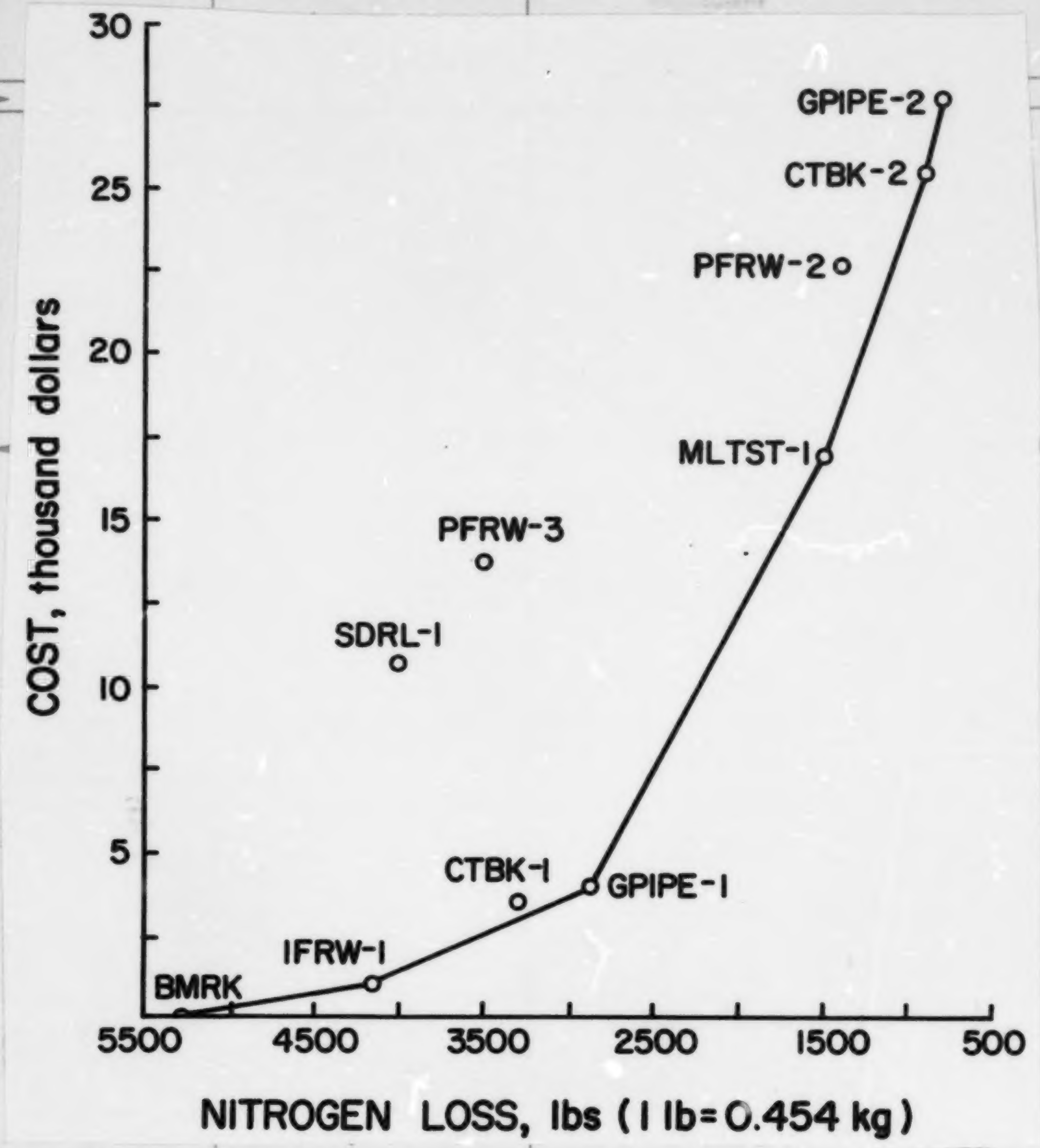

Figure 8. On-farm costs of reducing nitrogen loss using alternative control practices on Magic Valley Farm 1.

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EPA-287 (Cin.)
(4-76)

pattern while maintaining the remainder of the farm in the first irrigation system or cropping pattern. For example, reducing losses to 3,500 lbs (1,590 kg) in the most cost-effective manner might require that some fields be irrigated with the improved furrow system, while other fields are irrigated with a gated-pipe system.

The reader is reminded once more that the use of a control practice on less than the entire farm may cause its average cost to vary. For irrigation systems requiring capital investment, the average cost of abatement may increase due to inefficiencies associated with smaller irrigation systems. As an example, use of improved furrow and gated-pipe systems on different parts of a farm might result in larger per unit costs of abatement for each system than shown by the efficiency frontier of Figure 8.

Control practices with costs significantly above the efficiency frontier would be relatively cost-inefficient in reducing losses of nitrogen from the farm. The capital intensive side-roll irrigation system, for example, or a change in cropping pattern without an accompanying change in irrigation system, would be relatively inefficient in reducing nitrogen losses. Nitrogen losses associated with the side-roll irrigation system (4,000 lbs or 1,820 kg) would be similar to those of the improved furrow system. Converting to the side-roll system (SDRL-1), however, would cost the grower $11,000 rather than $1,000. Hence, the side-roll system would be relatively cost-inefficient in reducing nitrogen losses. Cropping Pattern 2 (PFRW-2) would reduce nitrogen losses by 74 percent, since potato production would be eliminated. For the same reason, however, the change in cropping pattern would reduce net farm income by $23,000, making this an expensive control practice. Cropping Pattern 3 (PFRW-3) would be even less effective in reducing nitrogen losses, since some potatoes would still be grown. Nitrogen losses would be reduced by 34 percent, while net farm income would be reduced by $14,000, placing this system considerably above the efficiency frontier curve.

There is an important aspect of Figures 7 and 8 that should be noted. The points on the efficiency frontier curve represent the average costs of achieving abatement at that level through use of a given control practice. They are not the marginal or additional costs of moving from one point to the next. In some cases it might be possible to superimpose one control practice upon another, such as combining improved management with one of the more efficient irrigation systems or with a different cropping pattern. The relative efficiency of such combinations may not always be apparent from illustrations such as Figures 7 or 8.

In some situations it would be more logical to choose a control practice because of its combined effect on abatement of

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sediment (including phosphorus) and nitrogen. The multi-set irrigation system would not be cost-effective in abating sediment alone, but it could provide effective concurrent abatement of both sediment and nitrogen, albeit at high cost. The side-roll sprinkler system would abate sediment losses more efficiently than the multi-set system, but without the same level of effectiveness in terms of nitrogen abatement. Grower preferences can also enter into control practice choices.

Slope and Soil Texture

Several alternative slopes and soil textures are also common in the Magic Valley, making it desirable to include other farm conditions in the study (Table 24). Table 28 illustrates the net returns, input use, water, sediment, phosphorus and nitrogen losses of two additional slope and soil conditions under current management and farming conditions. Farm 1 is the benchmark farm (previously described), with silt loam soil and 1.5 percent slope. Farm 2 is similar except that the slope is

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TABLE 28. NET RETURNS, WATER AND POLLUTANT LOSSES, AND INPUT USE FOR ALTERNATIVE SOIL AND SLOPE CONDITIONS WITH CURRENT MANAGEMENT AND FARMING CONDITIONS IN THE MAGIC VALLEY

Item	Unit	Farms 1	Farms 2	Farms 3
Net returns	$	67,453	67,520	64,611
Losses				
Runoff	ac-in a/	5,534	6,448	6,350
Deep percolation	ac-in	4,750	3,836	6,500
Sediment	tons	1,922	5,482	1,045
Phosphorus	lbs	5,522	15,350	2,926
Nitrogen	lbs	5,288	4,938	13,636
Input use				
Water	ac-in	18,280	18,280	20,840
Labor	hrs	1,140	1,140	1,749
Nitrogen fertilizer	lbs	27,620	27,270	31,900
Phosphorus fertilizer	lbs	9,500	9,500	9,500

Note: Farms are listed in Table 24. All farms have Cropping Pattern 1 (Table 25) and use the present furrow irrigation system (PFRW).

a/ 1 acre = 0.405 hectares; 1 inch = 2.54 cm; 1 ton = 0.908 metric ton; 1 pound = 0.454 kg.

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EPA-287 (Cin.)
(4-76)

increased to 2.5 percent. The increased slope has been assumed to increase field runoff by 5 percent (of applied water) and to decrease deep percolation by 5 percent. Hence, irrigation efficiency would remain unchanged. The increased runoff losses would result in sediment and phosphorus losses from Farm 2 nearly three times those of the benchmark. The decreased deep percolation, on the other hand, would result in 350 lbs (160 kg) less nitrogen loss.

Water, irrigation, labor and phosphorus fertilizer use would remain unchanged for Magic Valley Farm 2. Phosphorus losses would increase and, in reality, phosphorus fertilizer application should also increase. Due to insufficient data, however, such a refinement was not considered for this study. Nitrogen fertilizer requirements for Farm 2 would be reduced by 350 lbs (160 kg). As a result, net returns would be increased by $67. If phosphorus fertilizer utilization had been increased to reflect the greater phosphorus losses, however, the increased costs would at least partially offset the savings in nitrogen fertilizer.

Farm 3 is assumed similar to the benchmark except that the soil texture is sandy loam rather than silt loam. Since this soil is more coarse textured, the percent deep percolation has been estimated at an additional 5 percent of the water applied. The percent runoff was assumed to be equivalent for both farms, so the irrigation efficiency for Farm 3 was assumed to be 5 percent less than for the benchmark.

The change in soil texture would increase farm water requirements by 2,500 acre-in (2,570 ha-cm). Although the percent runoff was assumed to remain unchanged, the quantity of runoff would be increased by 800 acre-in (820 ha-cm). Despite this fact, sediment and phosphorus losses would be only about 50 percent as high as the benchmark, because of the less erosive nature of these sandy loam soils.

Deep percolation losses for Farm 3 would be 1,750 acre-in (1,800 ha-cm) greater than for the benchmark case. This, coupled with the lower denitrification losses for sandy loam soils, would result in nitrogen leaching losses for Farm 3 nearly three-fold higher than those of the benchmark farm. These greater nitrogen losses would require application of an additional 4,600 lbs (2,090 kg) of nitrogen fertilizer. Coarse textured soils also require more frequent irrigations than do fine textured soils, because of their lower water holding capacities. Hence, the irrigation labor requirement of Farm 3 was assumed to be 50 percent more than that of the benchmark farm. Increased nitrogen fertilizer and labor requirements would result in reductions to net returns of $2,842.

EPA-287 (Cin.)
(4-76)

UMATILLA AREA

Overview

The Umatilla area model farm was assumed to have 1,300 acres (590 ha) of cropland, with sandy soils and relatively level fields. Crops of the area are most commonly irrigated with center-pivot sprinkler irrigation systems. Only one model farm was used for this study area, since one soil texture is predominant and the quantity of deep percolation under sprinkler irrigation is relatively unaffected by minor changes in slope. It was assumed that field runoff did not occur, so sediment loss was assumed not to be a problem.

Table 29 presents alternative cropping patterns for the Umatilla area model farm. Cropping Pattern 1 is the benchmark case, typical of present-day cropping in this area. The remaining cropping patterns represent a substitution of various crops for late potatoes by 130-acre (59 ha) lots, the approximate size of traditional center-pivot irrigated fields. Since late potatoes require more water and nitrogen fertilizer than the remaining crops in the table, Cropping Patterns 2 and 4 would be expected to have lower levels of nitrogen loss than Cropping Pattern 1.

TABLE 29. CROPPING PATTERNS DEFINED FOR THE UMATILLA AREA MODEL FARM

	Cropping pattern			
Crop	1	2	3	4
	(acres) a/			
Alfalfa hay	520	520	520	520
Winter wheat	390	390	390	390
Field corn	0	0	0	260
Dry beans	0	0	130	0
Early potatoes	0	260	0	0
Late potatoes	390	130	260	130

a/ 1 acre = 0.405 hectares.

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EPA-287 (Cin.)
(4-76)

Control practices used on the Umatilla area model farm to reduce nitrogen losses are shown in Table 30. These alternative farming situations combine two irrigation systems, present center-pivot (PCP) and center-pivot with improved water management (ICP), with the cropping patterns shown in Table 29. The following sections present on-farm costs, and nitrogen-abatement effectiveness, of the control practices listed in Table 30.

Benchmark (BMRK-2)

Table 31 includes results for the Umatilla area benchmark farm. Deep percolation losses have been assumed to be 10 percent of water applied, or about 5,700 acre-in (5,860 ha-cm). This amount of water would transport 71,877 lbs (32,600 kg) of nitrogen below the crop root zone (Table 31). The farm would require 5,100 megawatt hours (MWH) of energy for pumping water to the farm and for on-farm pressurization. Net returns to water, land, management and overhead would be $313,228. It should be kept in mind that crop prices represent an average for the years 1975 to 1977, whereas crop production costs and input prices represent those prevailing in early 1978.

Irrigation System Change (ICP-1)

Current center-pivot irrigation systems have a relatively

TABLE 30. CONTROL PRACTICES USED ON THE UMATILLA AREA MODEL FARM

Control practice	Irrigation a/ system	Cropping pattern
BMRK-2 b/	PCP	1
ICP-1	ICP	1
PCP-2	PCP	2
PCP-3	PCP	3
PCP-4	PCP	4
ICP-2	ICP	2
ICP-3	ICP	3
ICP-4	ICP	4

a/ Present center-pivot (PCP) or improved center-pivot (ICP).

b/ Benchmark for the Umatilla area model farm.

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(4-76)

TABLE 31. NET RETURNS, WATER AND POLLUTANT LOSSES, AND INPUT USE FOR THE CONTROL PRACTICES USED ON THE UMATILLA AREA MODEL FARM

Item	Unit	BMRK2	Irrigation system change[a]	Cropping pattern changes[a]			Combination irrigation system & cropping pattern changes		
			ICP-1	PCP-2	PCP-3	PCP-4	ICP-2	ICP-3	ICP-4
Net returns	$	313,228	319,140	302,325	249,585	194,303	307,226	254,226	193,492
Cost	$	---	-5,912	10,903	63,643	110,925	6,002	59,011	114,736
Reduction in net returns	%	---	-1.9	3.5	20.3	37.9	1.9	18.8	36.6
Losses:									
Deep percolation	ac-in[b]	5,655	2,691	5,369	5,395	5,395	2,548	2,561	2,561
Nitrogen	lbs	71,877	34,788	57,291	57,733	49,725	28,548	28,249	24,648
Reduction in nitrogen losses:									
Quantity	lbs	---	37,089	14,586	14,144	22,152	43,329	43,628	47,229
Percent	%	---	51.6	20.3	19.7	30.8	60.3	60.7	65.7
Input use:									
Water	ac-in	56,550	53,820	53,690	53,950	53,950	50,960	51,220	51,220
Energy	MWH	5,080	4,835	4,823	4,847	4,847	4,578	4,602	4,602
Labor	hrs	1,131	1,131	1,027	1,001	845	1,027	1,001	845
Nitrogen fertilizer	lbs	219,960	182,910	193,700	187,200	167,700	164,710	157,690	142,350
Cropping pattern		1	1	2	3	4	2	3	4

[a] Cropping patterns as defined in Table 29 and control practices as defined in Table 30.

[b] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.; 1 pound = 0.454 kg.

EPA-287 (Cin.)
(4-76)

high irrigation efficiency (assumed to be 80 percent). The improved center-pivot irrigation system is assumed to make use of an irrigation scheduling service. Its efficiency is assumed to be 85 percent, with 5 percent deep percolation and 10 percent wind and evaporation losses. With use of the improved center-pivot, deep percolation losses would decline by over 50 percent, thereby reducing nitrogen losses by 52 percent (Table 31). Energy use would be reduced by 250 MWH and nitrogen fertilizer use by 37,000 lbs (16,800 kg). Use of improved management should not affect the irrigation labor requirement of the farm. Net returns would increase by $5,900, due to the reduced energy and nitrogen fertilizer requirements. These would more than offset the cost of the irrigation scheduling service (Table A-10).

Cropping Pattern Changes

Although the adoption of other cropping patterns would be effective in reducing nitrogen losses, reductions in net returns would be large compared to adoption of the improved center-pivot system (Table 31). Water requirements of the alternative cropping patterns should vary less than 5 percent from the benchmark. As a result, deep percolation losses would vary little. The variations in nitrogen losses would be primarily due to differences in nitrogen fertilizer use by the alternative cropping patterns.

Cropping Pattern 2 (PCP-2)--

Cropping Pattern 2 represents the substitution of two fields (260 acres or 105 ha) of early potatoes for late potatoes. Deep percolation losses would be reduced by 300 acre-in (310 ha-cm), because of the reduced water requirement of early potatoes. The energy and irrigation labor requirements would also be less than those of the benchmark, due to the smaller quantity of water applied. Nitrogen losses would be reduced by 20 percent, reflecting the lower quantities of deep percolation and the lower nitrogen fertilizer requirement of early potatoes. Net returns would decline by $11,000 or 3.4 percent, reflecting generally lower net returns from this crop.

Cropping Pattern 3 (PCP-3)--

Cropping Pattern 3 illustrates the effects of substituting one field of dry beans for late potatoes. Dry beans require less water and less nitrogen fertilizer than do potatoes. These factors would combine for a 20 percent reduction in nitrogen losses. The lower water requirement would also reduce pumping energy requirements by 233 MWH and irrigation labor requirements by 130 hours. The reduction in net returns of 20 percent can be attributed to the relatively low value of dry beans when compared to late potatoes.

EPA-287 (Cin.)
(4-76)

Cropping Pattern 4 (PCP-4)--
Cropping Pattern 4 represents a substitution of two fields of corn for late potatoes. Nitrogen losses would be reduced by 31 percent, due to reductions of deep percolation losses and nitrogen fertilizer use. Since field corn is a low-value crop relative to late pototoes, net returns would be 38 percent less than for the benchmark case.

Combination Irrigation System and Cropping Pattern Changes

Combining the improved center-pivot system with Cropping Patterns 2 through 4 would reduce deep percolation losses more than 50 percent below those of the corresponding present center-pivot, cropping pattern combination. As a result, water and energy use would decline roughly 2,700 acre-in (2,780 ha-cm) and 200 MWH, respectively, and nitrogen losses would be substantially reduced (Table 31). If the improved center-pivot was combined with Cropping Patterns 2 or 3, nitrogen losses would be reduced by an additional 40 percent, which represents a reduction in losses of about 60 percent when compared with the benchmark. Using improved irrigation management with Cropping Pattern 4 would reduce nitrogen losses an additional 35 percent, which represents a 66 percent reduction below the value of the benchmark. Cropping Pattern 4 also would have a smaller requirement of nitrogen fertilizer than Cropping Patterns 2 or 3, however. Consequently, combining the improved center-pivot with Cropping Pattern 4 still could not reduce nitrogen losses as much as for Cropping Patterns 2 or 3, since there was less opportunity for nitrogen loss abatement.

Net returns of the three cropping patterns would increase by $4,000 to $5,000 as a result of the savings in nitrogen fertilizer and energy for water pumped when using the improved center-pivot system. Compared to the benchmark, net returns would decline by $6,000 if improved irrigation management were used with Cropping Pattern 2. For Cropping Patterns 3 and 4, with improved irrigation management, net returns would be reduced $59,000 and $115,000, respectively. These larger differences are due primarily to the variation in quantity of potatoes produced.

A Comparison of Control Practices

The on-farm costs and nitrogen loss levels associated with the control practices of Table 31 are plotted in Figure 9. The least-cost method of reducing nitrogen losses from the benchmark level of 72,000 lbs (32,700 kg) to 35,000 lbs (15,900 kg) would be to use the improved center-pivot system (ICP-1). In addition, net returns would actually increase about $6,000, due to the lower expenditures for pumping energy and for nitrogen fertilizer. Costs of abatement beyond this point would require a substitution of crops, however, which can become very costly

EPA-237 (Cin.)
(4-76)

(Figure 9). For example, the substitution of two fields of early potatoes for late potatoes would reduce nitrogen losses to about 28,500 lbs (12,900 kg) at a cost of $6,000 to the grower (ICP-2). This represents an average cost of $0.14 per lb ($0.31 per kg) of nitrogen-loss reduction, but the marginal cost of abatement achieved by adding Cropping Pattern 2 would be about $1.85 per lb ($4.07 per kg) of nitrogen-loss reduction.

Reducing nitrogen losses from the farm below 28,500 lbs (12,900 kg) would be extremely costly. Further crop-mix changes would achieve little, despite reductions in net returns of 18 percent or more. Substituting one field of dry beans for a field of late potatoes (ICP-3) would reduce nitrogen losses to about 28,200 lbs (12,800 kg), for example, but the cost to the grower would be $59,000. Since nitrogen losses were reduced to 28,500 lbs (12,900 kg) at a cost of $6,000 (ICP-2), the additional reduction of about 300 lbs (140 kg) would cost the farm an additional $53,000, or about $175 per lb ($385 per kg) of additional nitrogen pollution abatement. Compare this to the use of an improved center-pivot system alone, where nitrogen losses could be reduced an additional 6,500 lbs (2,950 kg) at a cost of about $65,000, or $10 per lb ($22 per kg) of additional nitrogen-loss abatement.

Further reduction of nitrogen losses (to 25,000 lbs or 11,400 kg) could be accomplished by substituting two fields of corn for late potatoes (ICP-4). The cost would be $115,000, or a 37 percent reduction in net returns. This represents an average cost of $2.43 per lb ($5.35 per kg) of nitrogen-loss abatement. Compared to the use of improved irrigation management alone, Cropping Pattern 4 would reduce nitrogen losses by an additional 10,000 lbs (4,500 kg) at a cost of $126,000. This corresponds to $12.60 per lb ($27.75 per kg) of nitrogen saved.

The reader is reminded that the use of a control practice on less than the entire farm may cause its average cost effectiveness to vary. For example, suppose improved irrigation management was used only on late potatoes with Cropping Pattern 1. Compared to the benchmark case, net returns would actually increase by $4,773, while nitrogen losses would decline by 29,172 lbs (13,200 kg). In general, one should expect the relative increase in net returns to be greater if an irrigation scheduling service is used only on late potatoes, rather than on all crops. The per-acre cost of this service on late potatoes is nearly twice that for other crops (Table A-10), however, leaving the cost per unit of nitrogen abatement about the same whether the service is applied to the whole farm or just to the potatoes.

Below 35,000 lbs (15,900 kg) of nitrogen losses, the efficiency frontier curve between individual control practices can

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EPA-287 (Cin.)
(4-76)

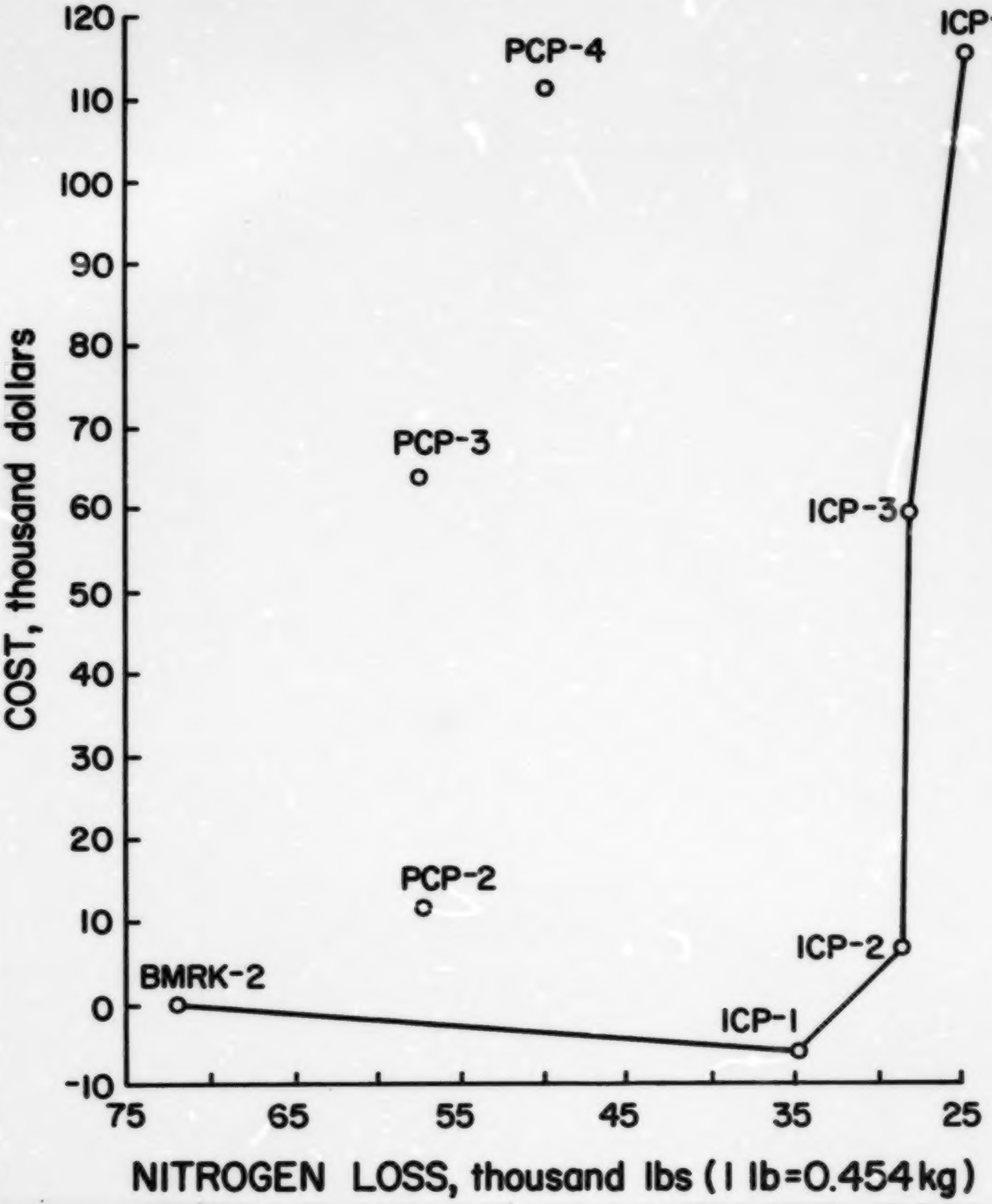

Figure 9. On-farm costs of reducing nitrogen loss using alternative control practices on the Umatilla Area model farm.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

no longer be construed to represent their combinations. This is because: 1) it is not possible to have less than the total farm using the improved center-pivot system and remain on the efficiency frontier curve, for all points on the curve require full-farm usage of this system; and 2) it is not generally possible to have cropping pattern changes of less than 130 acres (53 ha).

OTHER STUDIES

Two other studies of pollution abatement for irrigation return flows in the Pacific Northwest are worthy of mention at this point. Both have focused on the economic costs of pollution abatement in the Yakima River Basin of Washington. Each offers additional insights into the means and costs of pollution control programs. The first study, by Gossett (1975), applied a typical farm model (similar to that of Obersinner for the Magic Valley) to Yakima River Basin farming conditions. Pfeiffer (1975), in a second study, constructed a model representing the agriculture and hydrology of the entire river basin in order to assess costs and impacts of alternative abatement programs.

The Yakima Area

The Yakima River Basin, illustrated in Figure 10, lies in southcentral Washington and encompasses about 6,000 square miles (15,500 square km). The basin contains approximately 450,000 acres (180,000 ha) of irrigated land, most of which was originally developed through a series of Bureau of Reclamation irrigation projects. Average farm size, including many fruit orchards of less than 25 acres (10 ha), is less than 200 acres (80 ha). The more than 2,000 farms in the basin are organized into several independent irrigation districts. Therefore, any policies designed to improve water quality through modified agricultural activities in the basin will necessarily involve many farmers and will require considerable planning and administrative effort (Pfeiffer and Whittlesey, 1976).

Existing water rights in the basin have normally been sufficient for crop production. Thus, little incentive has been provided by water costs or supplies to improve irrigation efficiency through better management and/or capital expenditures (a notable exception being the drought period of 1976 to 1977, when several irrigation districts received only enough water to keep perennial crops and a few annual crops alive). Surface or rill irrigation is used on 60 to 70 percent of the irrigated land. The remaining acreage is irrigated by sprinkler irrigation methods adopted primarily in response to growing labor shortages and higher wages. A large proportion of the tree fruit acreage is irrigated with solid-set sprinkler systems. While some 80 different crops are commercially grown in the Yakima Basin, the economic returns and hydrologic characteristics of the basin can

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

be represented adequately by six to ten crops. A typical farm would grow no more than three to five crops.

Regions 1 and 2 (Figure 10) are dominated by forage crop production which supports an extensive livestock industry. Small grains, sugarbeets, and vegetables have also been traditional crops in Region 2. Sugarbeets will no longer be produced in this area, however, due to the elimination of processing facilities in Washington in 1979. Region 3 is a relatively small area above the city of Yakima in which diversified crop production prevails. Region 4, lying along the Naches River, is dominated by sprinkler-irrigated tree fruits. Regions 5, 6 and 7 are the largest and most intensively cultivated areas in the basin. Level land, rich deep soil, and favorable weather conditions make these regions suitable for almost all irrigated crops. Relatively large tracts of less productive land are used for forage crops and pasture, however.

Water quality in the Yakima River has been generally excellent above the city of Yakima. River nitrogen concentrations have remained below the algae bloom level of 0.30 mg/l during most the year. Temperature has usually remained below the Washington Department of Ecology Class A Standard of 65°F (18°C). Sediment loads have generally been small except during periods of heavy snow melt or precipitation. Similarly, the Naches River has generally met accepted water quality standards.

Approximately one-half of the 2.4 million acre-ft (300,000 ha-m) of water diverted annually from the river is used above Yakima and one-half below Yakima. As is evident from Figure 10, this implies a considerably higher per-acre usage of water along the upper reaches of the river. Below Yakima, water quality grows progressively worse as a result of major irrigation diversions and large return-flow volumes. It is estimated that 80 to 90 percent of the water in the lower reaches (6 and 7) is return flows from upper regions during the late summer months. These return flows carry a higher concentration of nitrogen and suspended solids than contained in upper river water. Consequently, nitrogen concentrations exceeding 1.0 mg/l and water temperatures exceeding 80°F (27°C) are frequent during the summer. Turbidity caused by suspended sediments and algae blooms afflict the lower reaches during most of the irrigation season, with their effects being most pronounced during the period from mid-July to mid-September when water flow is lowest and irrigation use is highest. During this period, low water quality inhibits fish passage and recreational activities, and turbidity causes problems with downstream sprinkler systems.

It is in this hydrologic and economic setting that the studies by Gossett and Pfeiffer were undertaken. Each study looked at theoretical water quality management practices which went beyond the application of typical control practices or best

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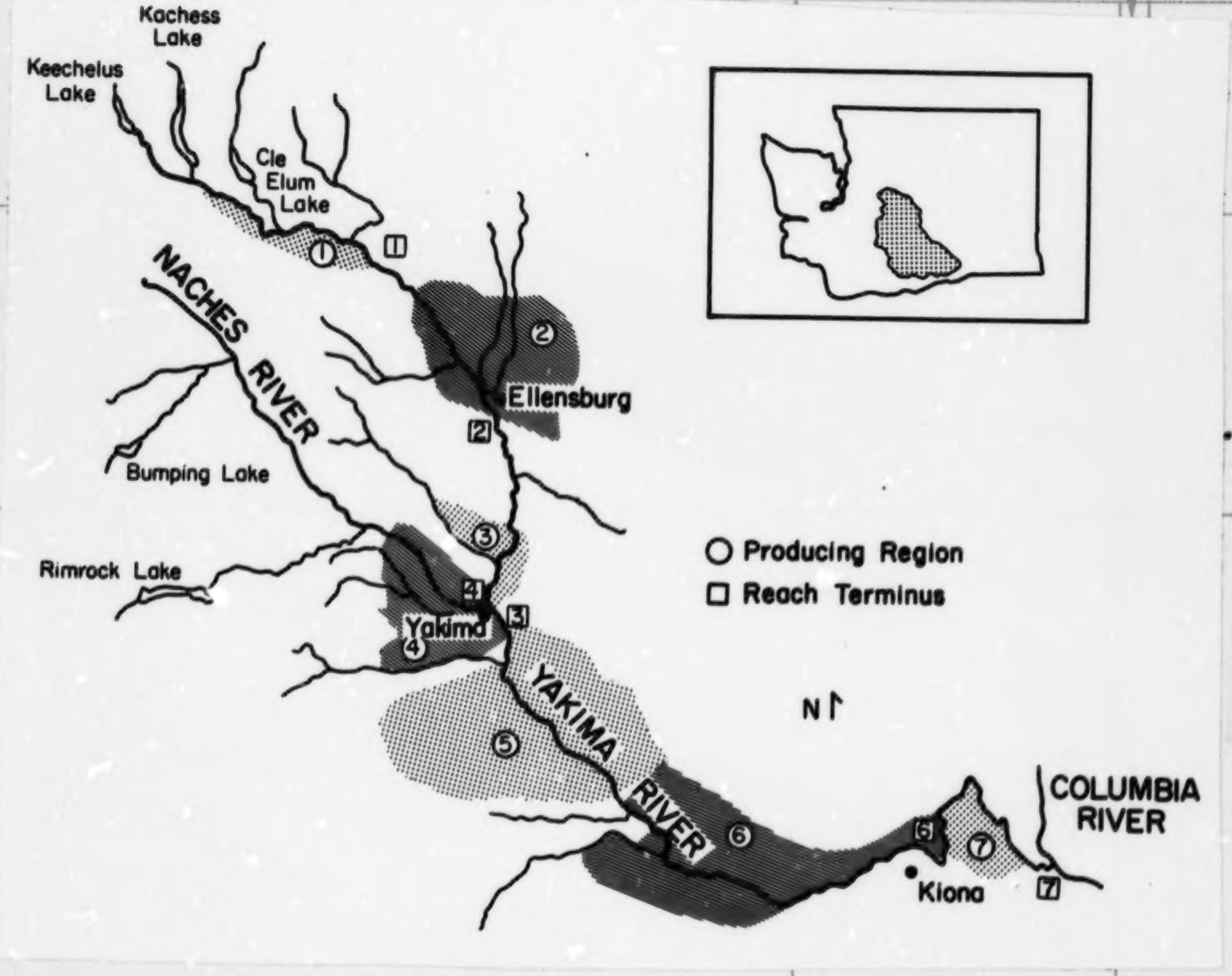
EPA-287 (Cin.)
(4-76)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Bumping Lake
Rimrock Lake
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Figure 10. The Yakima River Basin.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

management practices. Options available for abating irrigation return flow pollution included changes in irrigation systems and water management, and adjustments in farm cropping patterns. However, the policies used to "drive" these models (to induce the application of specified control practices) were not typical of those that would be applied in practice. For example, the Gossett and Pfeiffer models considered taxes on water and nitrogen to inhibit their respective usage, water rationing or water rights adjustments, and constraints on return-flow quantities or qualities. While many of these policies would probably not be feasible in actual practice, they provided a means of observing optimum adjustments to meet water quality standards. Theoretically, it should be possible to implement the same patterns of adjustment, such as changes in irrigation practices or cropping patterns, through subsidies, education, or legal constraints. Thus, while these studies used theoretical policies beyond the scope of most current 208 planning programs, they did indicate the most cost-effective means of pollution abatement or of meeting water quality standards in an actual river basin. It is with this background that the studies will be briefly described.

The Gossett Study

Gossett used linear programming to analyze adjustments on a representative farm in the Yakima River Basin, utilizing input data similar to that described in this report. The model[2] was able to predict the seasonal quantity of nitrogen leaving the farm in subsurface drainage and the amount of sediment carried by surface runoff. These losses were predicted for each of five crops, four fertilization rates, and six irrigation systems. Each crop, therefore, could be produced 24 possible ways, representing potential farm adjustments for pollution abatement.

Gossett's basic model portrayed a farm which had a total of 560 acres (230 ha) of gently sloping land and deep silt loam soil. The crop mix included potatoes, sugarbeets, wheat, spearmint, and alfalfa. The farm was irrigated by conventional gravity flow methods using siphon tubes and open ditches. The model maximized net farm revenue for a single production year. Costs included expenses for land and operator labor. Constraints were imposed to control crop rotations (Gossett, 1975; and Gossett and Whittlesey, 1976).

The six irrigation systems considered by Gossett included an existing surface system plus five alternative systems using

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[2] The term "model" refers to the typical farm construct being analyzed through the use of linear programming techniques. A unique model would be required to represent each different farming situation.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

varying amounts of labor and capital. The capital requirements and costs for these systems are summarized in Table 32. Irrigation System 1 represented the base level of irrigation management for a conventional surface-irrigated farm, using open ditches, siphon tubes, and furrows. This system served as a benchmark for comparison with other irrigation systems. Irrigation System 2 employed additional labor to reduce stream size once the stream had reached the field bottom, plus an improved

TABLE 32. CAPITAL INVESTMENT AND ANNUAL OPERATING COSTS OF SIX IRRIGATION SYSTEMS

Irrigation system	Capital investment a/	Annual operating cost a/, b/
	------- ($/ac) c/ -------	
1. The existing system. Surface irrigation with open ditches, siphon tubes, and a base level of irrigation management.	7.43	2.05
2. Same as the existing system except for improved irrigation management, including additional labor to cut-back furrow stream size.	7.43	2.05
3. Surface irrigation with a collection pond and pump to reuse tailwater.	18.16	7.82
4. Surface irrigation with an automatic reuse system using gated-pipe and moisture sensing devices.	145.00	23.05
5. Side-roll sprinkler with excellent irrigation management.	160.00	19.42
6. Solid-set sprinkler with excellent irrigation management.	645.00	73.57

a/ Costs reflects 1974 price levels.

b/ Excludes irrigation labor, water use charges, and electric power costs, but includes capital amortization costs and maintenance costs.

c/ 1 acre = 0.405 hectare.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

level of management. The improved management included optimal timing of irrigation and length of irrigation set. It was assumed that total water loss from System 2 would be one-half the loss from System 1.

Irrigation System 3 modified System 1 by reusing the tailwater and employing an improved level of management as described for Irrigation System 2. It was assumed that total water loss of System 1 could be reduced by 80 percent, and that runoff losses would be negligible. Irrigation System 4 was an automatic reuse system using gated-pipe and remote sensing devices to control stream flow and set time. It was assumed that total water loss could be reduced by 80 percent from that of System 1, and that runoff losses would be negligible. Irrigation System 5 was a side-roll sprinkler system operated with excellent irrigation management. Irrigation System 6 was a solid-set sprinkler system, also operated with excellent irrigation management.

Deep percolation loss was assumed to be a constant percentage of the amount of water applied for Systems 1 and 2. It was assumed to constitute the total loss for Systems 3 and 4, which utilized a form of pump-back irrigation. Deep percolation under sprinkler irrigation was assumed to equal the total loss minus 10 percent of the water applied, which represents the loss to wind and evaporation. Table 33 shows the estimated irrigation efficiencies and deep percolation losses which were utilized in the Gossett model.

Policy Options--

Policy options which were considered by Gossett for abating pollution included the following:

1. Constraining the total nitrogen outflow from the farm.
2. Placing a per-unit tax on nitrogen losses leaving the farm.
3. Making payments to the grower for nitrogen and sediment pollution abatement.
4. Constraining total sediment outflow from the farm.
5. Place a per-unit tax on sediment outflow from the farm.
6. Constraining the total use of nitrogen fertilizer on the farm.
7. Constraining the total use of irrigation water on the farm.
8. Placing a per-unit tax on nitrogen fertilizer applied.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 33. ESTIMATED IRRIGATION EFFICIENCIES AND DEEP PERCOLATION LOSSES BY CROP AND IRRIGATION SYSTEM, GOSSETT STUDY

Crop	Irrigation system 1	2	3	4	5	6
	- - - - - - - - Efficiencies (%)					
Potatoes	40.5	57.7	77.3	82.0	59.4	71.5
Sugarbeets	49.2	66.0	82.9	86.6	73.6	80.0
Wheat	46.3	63.3	81.2	85.2	70.5	78.1
Spearmint	40.5	57.7	77.3	82.0	64.2	74.4
Alfalfa	57.9	73.4	87.3	90.2	83.1	85.7
	- - - - - - Deep percolation (in.) a/					
Potatoes	12.9	9.1	8.5	6.4	15.0	7.5
Sugarbeets	13.2	9.8	7.4	5.6	8.0	4.5
Wheat	4.3	3.1	2.6	1.9	3.0	1.7
Spearmint	15.1	10.6	10.0	7.5	13.7	7.2
Alfalfa	13.7	10.8	6.4	4.8	3.7	2.2

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a/ 1 inch = 2.54 cm.

9. Placing a per-unit tax on water applied.

10. Paying the farmer for every acre of close-growing crops which he produced.

The first five policies are not admistratively feasible at present, unless all return-flow waters can be collected by a common drainage system and monitored. The policies can still be used to determine a norm to which other policies can be compared, however. Taxing or constraining sediment loss remains potentially feasible, but difficult to implement for individual farms.

Policies were first imposed on the farm in the short-run only, with investment in additional irrigation equipment not being allowed. The policies were also examined in the long-run,

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EPA-287 (Cin.)
(4-76)

where irrigation system changes would be feasible. Production costs were derived from cost studies conducted by the Cooperative Extension Service of Washington State University. Costs for irrigation labor, nitrogen fertilizer, and electric power were entered in the programming model at rates of $3.00 per hour, $0.20 per lb (40.44 per kg), and $0.085 per acre-in ($0.082 per ha-cm) of water, respectively. All costs and prices used for this analysis were representative of the mid-1970s in central Washington.

Gossett Study Results--

A benchmark solution was obtained when the farm was irrigated by the existing system, free of external constraints. The only internal constraints were restricted crop acreages in order to represent realistic crop rotations. These constraints were: potato acreage ≥ 80 (32 ha); sugarbeet acreage ≥ 140 (57 ha); alfalfa acreage ≤ 100 (41 ha); wheat acreage ≤ 140 (57 ha); and spearmint acreage > 140 (57 ha). The benchmark solution was the norm with which other solutions were compared.

When sediment and nitrogen overflows were unconstrained, the 560-acre (230-ha) farm produced a net revenue of $87,095, or $155.53 per acre ($384.02 per ha)(Table 34). Total nitrogen leached through the root zone was calculated at 52.5 lbs per acre (58.8 kg/ha), producing a nitrogen concentration in the sub-surface drainage water of 21.3 ppm. The benchmark also had 1,922 tons (1,477 mt) of sediment leaving the farm, or 3.34 tons

TABLE 34. BENCHMARK SOLUTION, YAKIMA VALLEY MODEL FARM

	Units	Total	Per acre a/
Net revenue	$	87,095	155.53
Nitrogen losses	lb	29,407	52.51
Sediment yield	tons	1,922	3.43
Nitrogen applied	lb	139,500	249.10
Water applied	ac-in	35,274	63.00
Irrigation labor	hrs	1,990	3.55
Deep percolation	ac-in	6,349	11.30
Runoff	ac-in	12,225	21.80

a/ 1 acre = 0.405 hectare; 1 pound = 0.454 kg; 1 ton = 0.908 metric tons; 1 inch = 2.54 cm.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 35. COMPARISONS BETWEEN ALTERNATIVE IRRIGATION SYSTEMS, YAKIMA VALLEY MODEL FARM

Irrigation system	Nitrogen leached (lb)[a]	Nitrogen concentration (ppm)	Sediment yield (tons)	Sediment concentration (ppm)	Net revenue ($)	Opportunity cost[b] ($)	Resource use		
							Nitrogen (1,000 lb)	Water (ac-in)	Labor (hrs)
1. Surface existing	29,407	21.3	1,922.6	1,388	87,095	0	139.5	35,274	1,990
2. Surface cut-back	22,065	21.3	736.4	1,408	83,618	3,477	128.7	25,987	3,980
3. Surface tailwater reuse	19,763	23.9	0	0	87,801	706[c]	128.7	20,415	1,990
4. Surface automatic reuse	15,366	24.3	0	0	84,069	3,026	121.2	19,486	80
5. Sprinkler side-roll	24,319	23.8	0	0	78,034	9,061	128.7	23,529	796
6. Sprinkler solid-set	14,783	26.7	0	0	54,196	32,899	121.2	21,226	80

[a] 1 acre = 0.405 hectare; 1 pound = 0.454 kg.; 1 ton = 0.908 metric tons; 1 inch = 2.54 cm.

[b] Reduction in initial revenue due to changing the irrigation system.

[c] A net increase in farm profits as a result of this set of management practices.

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EPA-287 (Cin.)
(4-76)

per acre (7.48 mt/ha). A total of 63 in (160 cm) of water would be applied per acre of cropland, with resultant deep percolation and runoff losses of 11.3 and 21.8 in (28.7 and 55.4 cm), respectively.

The effects of alternate irrigation systems for the Yakima Valley model farm are compared with the benchmark in Table 35. These solutions imposed no constraints or economic inducements to influence pollution abatement beyond those provided by the irrigation system. Comparing the existing system with System 2, one can see that improved management would reduce nitrogen leaching by 25 percent and sediment yield by 62 percent at a total farm cost of $3,477, or $6.20 per acre ($15.31 per ha). This cost arises because the additional labor is more expensive than the savings in fertilizer use. The 3,900 hours required to irrigate the 560 acres (230 ha) with System 2 would utilize three to four full-time irrigators. Consequently, farm operators would generally adopt more capital-intensive irrigation systems in order to reduce required labor.

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Surface tailwater reuse, System 3, was able to further reduce nitrogen leaching losses below those of System 2, and to completely eliminate sediment discharge. The reduced nitrogen losses may have been an artifact, however, because deep percolation was assumed by Gossett to be a constant proportion of the amount of water applied. With this particular system, water would remain in the irrigation furrows for the same length of time as for the benchmark, even though total water usage would be less because of the "capturing" of normal runoff losses. Total net revenue was increased slightly for this set of assumptions, because nitrogen fertilizer savings were greater than the increased costs of the tailwater reuse system.

A surface automatic reuse method, System 4, would allow significant reductions in nitrogen fertilizer, water, and labor use, while maintaining constant production. More efficient use of inputs would allow System 4 to be adopted at the relatively small cost of $3,026, or $5.40 per acre ($13.33 per ha). This is despite a required capital investment of at least $150 per acre ($370 per ha), because nitrogen leaching would be reduced to only 48 percent of the benchmark level when using this system.

The side-roll sprinkler, System 5, proved to be exceptionally costly. Adoption of this system would cost over $9,000 annually while still producing 24,319 lbs (11,000 kg) of leached nitrogen. Similar abatement reductions could be obtained at smaller private cost with other irrigation systems. The solid-set sprinkler, System 6, could reduce leached nitrogen by 50 percent, but only at a cost of $32,899, or $59 per acre ($138 per ha). Both of the sprinkler systems would seemingly be inefficient in reducing nitrogen losses to acceptable levels.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The above comparisons are valid only under the conditions assumed for this model. Increases in the value of fertilizer, water, or labor could cause some shifts in comparative advantage among the various irrigation systems. Also, changes to more sandy soils or steeper slopes would automatically reduce the advantages of surface irrigation systems over sprinkler systems. Under the conditions assumed, however, a farmer operating in this environment with perfect knowledge and complete mobility of resources would elect to irrigate with System 3, the surface tailwater reuse system, which maximizes his net revenue.

Gossett also looked at additional soil type and slope conditions in the Yakima region. Figure 11 summarizes the marginal abatement costs for estimated nitrogen leaching on alternate soil types in this area. Costs of abatement could quickly reach $2 per lb ($4.50 per kg) of nitrogen loss abatement if nitrogen leaching were to be reduced below 50 percent of current levels for the model farms. These estimated abatement costs are based on Gossett's estimates of the most efficient combinations of new irrigation methods, management inputs, and crops for each level of abatement.

Sediment yield is a function of only one production input, water. Thus, controlling water use is the most economically effective method of controlling most sediment losses. Under any policy to induce sediment abatement, such as taxing sediment, constraining sediment, constraining water use, or taxing water, the farmer would probably make the following adjustments: as allowable sediment levels were reduced, the farmer would first convert his total acreage to System 2, thereby reducing sediment outflow by 60 percent. This adjustment would have a total cost of about $3,000. To reduce sediment loss still further, the farmer would find it most profitable to substitute close-growing crops for row crops. A subsidy to the farmer would probably be required to induce such crop substitutions. A sediment outflow from the farm of 400 tons (360 mt), or an 80 percent reduction, would cost about $17,000 for the combination of practices. Minimum outflow from the farm for the conditions examined (29 tons or 26 mt) would be obtained by eliminating row crops. If sediment were the primary focus of abatement, it would be less costly in the long-run to turn to tailwater-reuse systems or sprinkler systems instead.

The Gossett study showed that a policy of subsidizing the farmer for increased acreage of close-growing crops at the expense of high-value row crops would necessitate an unreasonably large subsidy. Due to the large returns from row crops relative to close-growing crops in this case, the farmer would probably not be willing to alter his crop mix until subsidies exceeded $140 per acre ($350 per ha). Even this level of subsidy would not be particularly efficient in reducing sediment yield. It is probably not practical to attempt crop pattern adjustments

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

through subsidy programs of this type.

The Pfeiffer Study

This study is described because it represents an attempt to simultaneously study water quality control in an entire river basin. The approach included information derived from typical farm models, such as those described earlier in this report, but concentrated on the effects of on-farm pollution abatement practices on the quality of receiving waters. This approach showed that the specific water quality effects of control practices applied to different parts of a river basin would differ depending upon the location of their application. This type of information permits the design of more rational and efficient pollution-abatement programs. The focus is on stream water quality rather than on edge-of-field losses, which may not be directly or obviously linked with stream water quality.

Pfeiffer (1975) constructed models of agricultural sector water quality for the Yakima River Basin. Model segments are reflected schematically in Figure 12. He divided the river into seven reaches (Figure 10), with an associated land area corresponding to each river reach. In most cases, return flows from

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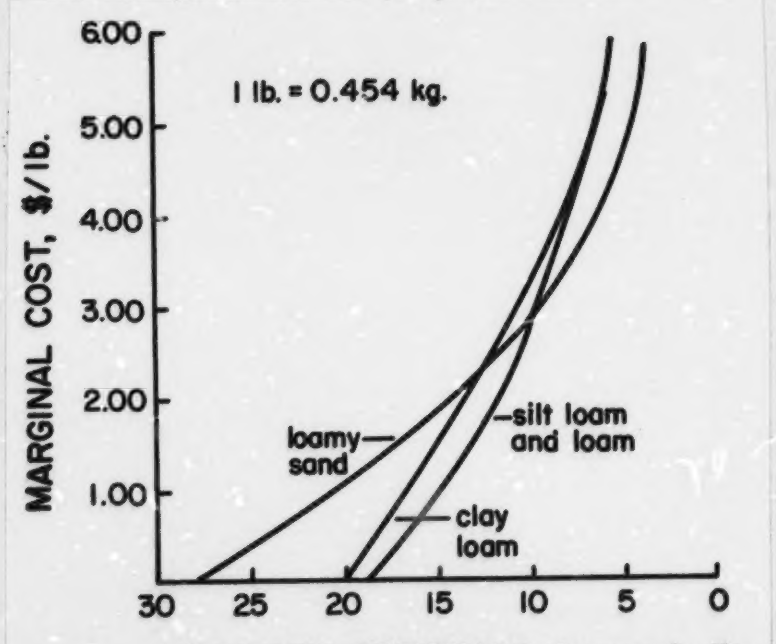

Figure 11. Marginal costs of abating nitrogen leaching for various soil types in the long run.

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EPA-287 (Cin.)
(4-76)

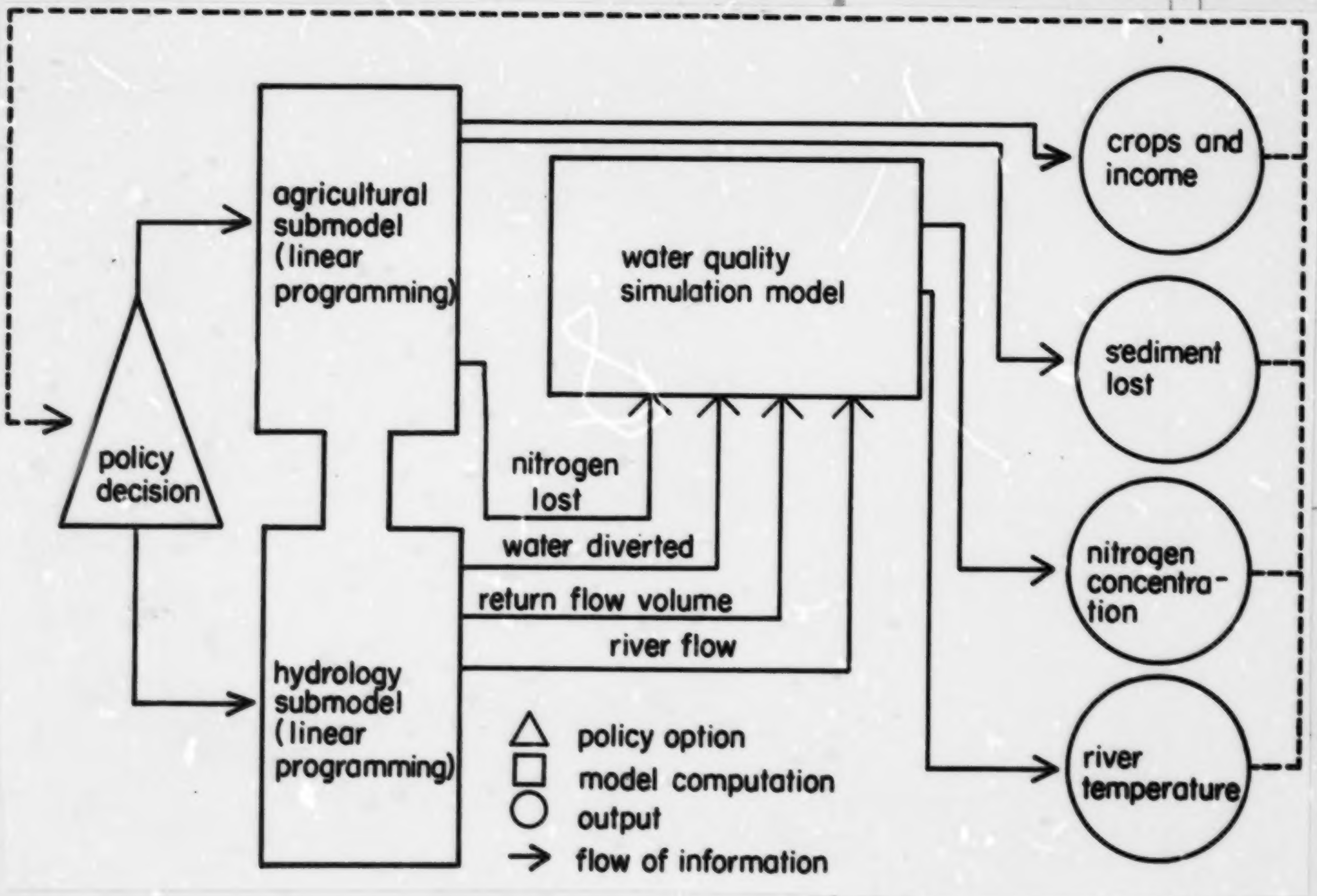
policy decision
agricultural submodel (linear programming)
hydrology submodel (linear programming)
water quality simulation model
nitrogen lost
water diverted
return flow volume
river flow
crops and income
sediment lost
nitrogen concentration
river temperature
△ policy option
□ model computation
○ output
→ flow of information

Figure 12. Schematic diagram of the Pfeiffer model for the Yakima River Basin.

the farming region drain into the respective river reach.

The agricultural-hydrology model adopted by Pfeiffer reflected sediment and nitrogen concentrations, and temperature, of the Yakima River throughout the basin. In particular, the model predicted nitrate and sediment losses as well as irrigation return-flow quantities for the farming sector. Lastly, the model integrated effluent discharges with water quality in a hydrology model of the Yakima River.

The Agricultural Submodel--

Pfeiffer's agricultural submodel for the river basin included ten crops, three irrigation systems, 11 regions and subregions, and four levels of nitrogen application for most crops. In order to permit some degree of regional specialization, row crop and fruit crop acreages were permitted to increase by 25 percent and 50 percent, respectively, within each region. The total acreage of these crops throughout the basin was constrained to present levels, however. The acreage of forage crops was not specifically restricted. The submodel reflected surface and subsurface return flows from crop activities within each region.

The data requirements for this type of analysis are similar to those described earlier in this section. Sediment losses were adjusted for factors such as crop cover, tillage practices, method and rate of irrigation, slope, soil type, and overall management level. Water rights in the river basin were assumed to represent maximum allowable diversions of water. In most cases, water quantities were more than sufficient to supply crop needs under current irrigation practices. By imposing constraints and/or higher prices on inputs used by the agricultural sector, abatement effectiveness and the distribution of abatement costs resulting from alternative policies could be estimated and compared.

The Hydrology Submodel--

Pfeiffer's linear programming model included a hydrology submodel representing river flows in the basin. This hydrology model reflected effects of water demands and return flows from the agricultural submodel on river flows. Irrigation diversions and deliveries at each reach terminus,and irrigation return flows carrying pollutants to the river, were included in the model. The net flow of water at each reach terminus was taken as the sum of water inflows minus water outflows for that reach. Natural inflows were included by individual river reach, and diversion rights were allocated by canal for each irrigation system of the river basin. In cases where canals serve more than one region, the activities were appropriately subdivided. Water flows in each major reach of the river were considered for the period from April through September. August, the period of lowest flow and most serious water quality problems, was used as a test on attainment of water quality standards. Municipal water diversions and return flows were also estimated as part of the hydrology submodel. The effects of municipal return flows were considered in the predictions of water quality.

Water Quality Simulation Model--
Pfeiffer's water quality simulation model was linked with the linear programming model as illustrated in Figure 12. This model measured, for example, the effects of nitrate concentrations contributed by irrigation return flows. It was found that not all nitrogen entering return-flow channels from individual farms arrives at the river. Some nitrogen is lost through denitrification or by transformation to organic forms during plant and phytoplankton consumption. Once in the river, phytoplankton utilization of NO_3-N continues. Part of the nitrogen is diverted with the irrigation water for additional use on farm lands, and part remains in the river as inorganic NO_3-N. Thus, the nitrogen concentrations in the river depend upon nitrogen losses from upstream farms, denitrification, plant and phytoplankton uptake, subsequent irrigation diversions, and the volume of water in the river itself.

The simulation model measured the flow of water and nitrogen throughout the various reaches of the river, adding and subtracting nitrogen and water as they were discharged into and diverted from the river. It was estimated that an average of only about 32 percent of the nitrogen lost from farms actually enters the river in nitrate form during the irrigation season. During August, this figure is reduced further to approximately 24 percent, because of plant and phytoplankton uptake.

Sediment losses were estimated by the agricultural submodel. Turbidity of the river resulting from this sediment loss was not estimated, however, because turbidity is a function of additional factors, including algae population, background water color, and municipal and industrial discharges.

Pfeiffer Study Results--
Environmental quality goals used for this study included a maximum nitrogen concentration of 0.3 mg/l in the river, a maximum river water temperature of 70°F (21°C) in August, and a maximum sediment loss of 1 ton per irrigable acre (2.2 mt/ha) throughout the basin. Improving irrigation efficiency to solve water quality problems required investments in new irrigation systems, improvements in irrigation management, or changes in crop mix or location of crop production within the basin. Table 36 is a brief comparison of the policies selected for analysis by Pfeiffer. The numbers shown in the table are solution numbers which will be described in greater detail below.

Two solutions were used in the Pfeiffer model to establish a basis for comparison of environmental improvement policies,

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 36. POLICIES SELECTED BY PFEIFFER FOR ANALYSIS

Policy	No change[a]	Regional crop area constraints relaxed[b] (benchmark)	Management improvement	N tax	water charge	Water rights reduction	Surface runoff forbidden
No change[a]	1						
Regional crop area constraints relaxed[b]		2					
Management improvement			3				
N tax				4			
Water charge				7	5		
Water rights reduction				8		6	
Surface runoff forbidden							9

NOTE: Numbers in cells are solution numbers designated for each policy analysis.

[a] Area of each crop in each region constrained to historical levels.

[b] Area of pasture and alfalfa unconstrained; field crop area constraints increased 50 percent; and row, fruit, and vegetable crop area constraints increased 25 percent in each region. Basin-wide area of each crop constrained to historical levels.

Table 37. Solution 1 constrained crop acreages in all regions to presently existing levels. This solution most accurately reflects current conditions in the basin. Solution 2 permitted regional crop production specialization by allowing a 25 percent increase in row, fruit, and vegetable crop acreage, a 50 percent increase in field crop acreage, and an unlimited increase in forage crop production for each region. Basin-wide acreages of each crop were still constrained to existing levels, however. Minor changes in crop distribution, income, and environmental quality still occurred with Solution 2, because of the difficulty of including all realistic constraints faced by farmers in the area. The results of Solution 2 were used as a benchmark with which to compare all remaining policy results.

TABLE 37. INCOME, RESOURCE USE, AND RESULTANT WATER QUALITY FOR PFEIFFER'S SOLUTIONS 1 AND 2

Item	Unit	Solution 1	 2
Net crop income	$1,000	105,950	106,910
Acres irrigated a/	1,000 ac	453	453
N applied, total	1,000 lbs	94,581	94,549
N applied per acre	lbs	209	209
N lost, total	1,000 lbs	16,523	16,389
Water diverted	1,000 ac-ft	2,403	2,393
Flow at Kiona, August	1,000 ac-ft	102	100
N concentration, season b/	mg/l	0.70	0.65
N concentration, August c/	mg/l	0.93	0.87
Sediment loss, total	1,000 tons	673	787
Sediment loss/irrigated acre	tons	1.49	1.74
Maximum temperature	°F	75.3	75.5

a/ 1 acre = 0.405 hectare; 1 pound = 0.454 kg; 1 foot = 30.48 cm; 1 ton = 0.908 metric tons.

b/ Average monthly maximum concentration for irrigation season.

c/ Maximum concentration.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 38. SUMMARY OF PFEIFFER'S BENCHMARK SOLUTION AND OF SOLUTIONS MEETING YAKIMA RIVER NITROGEN AND TEMPERATURE GOALS

Item	Unit	Solution							
		2[a]	4	5	6	7	7	8	8
N tax	$/lb[b]	---	.60	---	---	.20	.40	.20	.40
Water charge	$/ac-ft	---	---	20	---	10	5	---	---
Water rights reduction	%	---	---	---	50	---	---	40	30
Crop acreage	1,000 ac	453	420	261	288	296	296	322	371
Crop sales	$1,000	303,906	264,544	260,537	251,905	265,926	264,933	261,734	269,060
Net crop income	$1,000	106,910	62,972	78,959	90,317	75,233	68,350	81,757	72,796
Net producer cost	$1,000	---	43,938	27,951	16,593	31,676	38,560	25,153	34,114
Net social cost	$1,000	---	13,164	11,894	16,593	9,664	10,149	12,431	10,508
N applied, total	1,000 lb	94,804	51,289	70,334	68,302	60,101	58,392	63,609	59,016
N applied per acre	lb	209	122	269	237	203	198	198	159
N lost, total	1,000 lb	16,389	7,358	10,355	9,780	8,671	8,028	9,626	8,953
Water diverted	1,000 ac-ft	2,393	1,916	1,069	1,219	1,344	1,356	1,464	1,679
Flow at Kiona, August	1,000 ac-ft	100	176	251	228	219	220	170	187
N concentration, season[c]	mg/l	0.65	0.26	0.28	0.29	0.26	0.25	0.28	0.27
N concentration, August[d]	mg/l	0.87	0.28	0.28	0.30	0.27	0.26	0.30	0.30
Sediment lost, total	1,000 tons	787	546	92	107	227	273	127	478
Sediment lost per irrigated acre	tons	1.74	1.30	0.35	0.37	0.77	0.92	0.40	1.29
Sediment lost per irrigable acre	tons	1.74	1.21	0.20	0.23	0.50	0.60	0.21	1.06
Maximum temperature	°F	75.5	69.8	67.6	67.8	68.5	68.5	68.6	69.1

[a] Benchmark solution.
[b] 1 pound = 0.454 kg.; 1 acre = 0.405 hectare; 1 foot = 30.48 cm.; 1 ton = 0.908 metric tons.
[c] Average monthly maximum concentration for the irrigation season.
[d] Maximum concentration.

EPA-287 (Cin.)
(4-76)

Table 38 shows a summary of the policies evaluated by Pfeiffer at levels which met the environmental quality goals established for the study. The table also includes a summary of benchmark Solution 2 for comparison. Two measures of abatement costs were used for this study. "Producer cost" measured the reduction of farm income caused by abatement policies. In other words, this measure reflected the immediate and direct impact on agriculture. "Net social cost" measured the public or total cost of abatement policies. The two would differ if a transfer of income from agriculture to the public (a tax) or from the public to agriculture (a subsidy) was involved. Comparing the social costs of alternative policies is a more realistic measure of their relative economic efficiencies.

Solution 3 does not reflect a well-defined policy, since it resulted merely from a change in the assumptions regarding irrigation efficiency on current irrigated farms. This solution allowed surface irrigation efficiencies to increase by 10 percent, with tailwater reuse and sprinkler irrigation system efficiencies increasing by 5 percent. In essence, this solution reflected an improvement in management without changes in structures or additional investment for irrigation systems. The results of such improved management are shown in Table 39.

Solution 4 measured the effects of a tax on nitrogen fertilizer to abate pollution from nitrates in return flows. This policy was chosen because nitrogen loss is primarily a function of nitrogen application rate. The varying tax ranged from $0.10 to $0.70 per pound ($0.22 to $1.54 per kg) of nitrogen fertilizer. The linear programming technique provided means of measuring optimal use levels of farm inputs for any given level of costs. Obviously, nitrogen application rates declined as the tax increased. Fertilizer use was reduced on all crops at the higher tax rates, but reductions on irrigated pasture (a relatively low-value crop) were most pronounced. A nitrogen tax above $0.40 per pound ($0.88 per kg) resulted in no nitrogen fertilization of pasture in the basin. Water diversions declined with irrigated acreage, so less production of low intensity pasture caused August river flow volume to increase. Nitrogen concentration and water temperature goals were finally met with a nitrogen tax of $0.60 per pound ($1.32 per kg).

Solution 5 imposed a charge on the use of irrigation water ranging from $5 to $25 per acre-ft ($40 to $200 per ha-m). Use of water for irrigation reduces river flow, which in turn increases the effective concentration of pollutants and the river water temperature. Moreover, nitrogen loss is functionally related to the volume of deep percolation, and sediment loss is functionally related to the volume of runoff water. Irrigated pasture was once again the crop most affected, though alfalfa acreage also declined sharply at the $20 per acre-ft ($160 per ha-m) rate. The acreage of other crops remained relatively

EPA-287 (Cin.)
(4-76)

TABLE 39. INCOME, RESOURCE USE, AND WATER QUALITY DETERMINED WITH IMPROVED MANAGEMENT, PFEIFFER'S SOLUTION 3

Item	Unit	Solution 2 a/	 3
Net crop income	$1,000	106,910	108,332
Acres irrigated b/	1,000 ac	453	453
N applied, total	1,000 lbs	94,549	94,609
N applied per acre	lbs	209	209
N lost, total	1,000 lbs	16,389	14,232
Water diverted	1,000 ac-ft	2,393	2,207
Flow at Kiona, August	1,000 ac-ft	100	111
N concentration, season c/	mg/l	0.65	0.54
N concentration, August d/	mg/l	0.87	0.69
Sediment loss, total	1,000 tons	787	376
Sediment per irrigated acre	tons	1.74	0.83
Maximum temperature	°F	75.5	74.0

a/ Benchmark solution.
b/ 1 acre = 0.405 hectare; 1 pound = 0.454 kg; 1 foot = 30.48 cm; 1 ton = 0.908 metric tons.
c/ Average monthly maximum concentration for the irrigation season.
d/ Maximum concentration.

unchanged, though changes to more efficient irrigation methods were induced.

Solution 6 imposed a uniform percentage reduction of water rights to all regions, with the reductions varying from 10 percent to 60 percent of current levels. Sales or exchanges of water rights between regions were not permitted. This policy should result in efficient resource allocation only if the demand for water is the same in all regions before and after water rights are reduced. The major advantage of reducing water rights is the fact that the policy does not require a direct income transfer from agriculture to the public sector. Under this policy, as would be expected, irrigated acreage declined

EPA-287 (Cin.)
(4-76)

rapidly as water rights were reduced, primarily affecting crops in the order of their value. Water conserving irrigation systems were also implemented with increasing frequency as water rights were reduced. Water rights reductions of 30 percent or more even caused fruit production to decline in some areas.

Solution 7 combined a tax on nitrogen ranging from $0.20 to $0.40 per lb ($0.44 to $0.88 per kg) with a charge on water ranging from $5 to $20 per acre-ft ($40 to $160 per ha-m). Since both water and nitrogen contributed to pollution through irrigation return flows, it was expected that a combination of policies would be more efficient than policies directed at either individually. Solution 8 was similar, combining a tax on nitrogen ranging from $0.20 to $0.40 per lb ($0.44 to $.088 per kg) with a reduction in water rights from 10 percent to 50 percent throughout the area.

Solution 9 evaluated the effects of forbidding the discharge of surface runoff water by requiring sprinkler or tailwater reuse irrigation systems. The result was almost no change in cropping pattern, and only a small reduction of income compared with the benchmark solution. Sediment loss was completely eliminated, but river flow volume, nitrogen concentration, and water temperature changed little. This solution illustrated a policy directed at a single effluent, sediment, without affecting other major pollutants in the river basin. Thus, it has been shown that it is possible to completely abate one pollutant in a river basin without significantly affecting other water quality parameters. The major shortcoming of this policy was the fact that it had almost no impact on nitrogen concentration or water temperature, which are also serious problems in the basin. In such a situation, it would be possible to make large expenditures for abating one pollutant while not really improving water quality, if other pollutants remained unchanged.

Conclusions From Pfeiffer's Study--

Economic efficiency (cost effectiveness) is an important criterion by which to measure water quality improvement. It indicates the degree to which optimum resource use is attained while satisfying environmental quality standards. Though the structure of this study did not allow direct constraints of water quality characteristics in order to establish the minimum social cost, economic theory shows that optimal abatement is possible with taxes or with constraints on inputs which contribute to a particular pollutant. Nitrogen content of return flows, for example, would be most efficiently controlled with a policy affecting nitrogen fertilizer and irrigation water use. Water temperature, on the other hand, is a function primarily of river flow volume. Hence, policies reducing water diversions would be most efficient in affecting this quality parameter. Sediment loss, a function of surface water runoff, would be most efficiently controlled by irrigation systems which reduce or

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PAGE NUMBER
EPA-287 (Cir.)
(4-76)

eliminate runoff volumes.

Tables 38 and 39 showed that improved management, Solution 3, was unable to meet the water quality standards which were sought for this river basin. Each of the other solutions, Solutions 4 through 8, was able to meet water quality standards at varying levels of efficiency. In all cases, the net social costs of meeting water quality standards in the river basin were rather large. The most efficient policy was Solution 7. It included a combination of water charge and nitrogen tax in order to meet desired water quality standards at a net social cost of $9 million for the river basin. The least efficient policy in meeting all quality standards was Solution 4, which taxed only nitrogen. This policy resulted in a net social cost of over $13 million. Net farm income would actually be decreased by even larger amounts in each case, due to the additional charges to farmers for water and fertilizer.

The net social cost figures include required subsidies that must be paid to agriculture in order to meet specified water quality standards. To induce similar changes in cropping patterns, nitrogen fertilization levels, or irrigation systems through subsidy programs would require annual costs equal to net social costs. It is doubtful that benefits achieved through improvements of water quality to such levels would equal the costs imposed.

Though having the highest social cost, Solution 6 also resulted in the lowest producer cost. It was some $8.6 million less expensive to producers than the next least expensive policy, Solution 8. The fact that no taxes or charges were levied accounts for the low costs to producers imposed by this solution.

If subsidies could not be used to meet environmental standards, a reduction of water rights would probably be considered the next most acceptable solution by the farm sector, though the capital investment required for improved irrigation systems would be large. The only policy not requiring extensive capital investment for irrigation systems would be Solution 4. This policy had the highest producer costs of any policy evaluated, however. It would probably not be a politically acceptable way of meeting the proposed environmental standards.

Because of relatively low value, the production of irrigated pasture, alfalfa, and corn was the first to be reduced by all abatement policies. It is inevitable that the livestock industry, which was not included in the analysis, would decline markedly as feed production declined under such policies. It is also possible that farm income would be affected to a larger degree than indicated by the model results, because livestock was not included in the analysis.

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Labor employment in the farm, agricultural supply, and agricultural processing sectors would decline under all policies analyzed. In addition to farm output, the adoption of improved irrigation systems would lower irrigation labor demand. Reduced farm income and its impact on the economy would also diminish nonfarm employment opportunities.

The Pfeiffer study showed that it is possible to improve water quality in a river basin by controlling agricultural inputs or activities. Improvement to a point where water quality is suitable for virtually all uses of the Yakima River required a reduction of farm income ranging from 16 to 41 percent, depending on the policy employed. In addition to reduced farm income, these policies would impose burdens on the agricultural sector in the form of reduced land values, diminished livestock numbers, decreased activity in the agricultural supply and food processing industries, decreased agricultural employment, and increased capital investments in new irrigation systems.

It should be noted that the costs of abatement alluded to in this analysis are accurate only as relative values among alternative policies. The real cost of any policy might vary from that presented because of changes in crop input cost, crop prices, administrative program cost, and level of abatement desired.

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The historic pattern of water use in the Yakima River Basin has promoted irrigation methods and practices which are not conservative of water. The policy of providing water at a fixed cost per acre encourages the substitution of water for management, labor, and other farm inputs. This has led to unnecessarily high amounts of surface runoff and deep percolation loss, depleting river flow and resulting in water quality degradation. Under these circumstances, any policy which could alter the manner of water use would greatly improve irrigation efficiency and river water quality.

A large part of the irrigated pasture in the basin provides only small returns to producers, and is unsuitable for more intensive crop production. Retirement of this irrigated land from production would greatly improve water quality at a relatively small cost. It might be possible, for example, for a public agency to purchase the water rights to such lands for abatement purposes. In addition, there are undoubtedly other policy options or technological adoptions which were not considered in this analysis and yet which could become feasible alternatives to those considered.

The ultimate choice of policies to control water pollution depends on many factors. Efficiency should be of major concern, but the distribution of costs between the private and public sectors will probably carry greater importance in the political

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DISCUSSION

The study results reported in this section demonstrate that it is possible to abate sediment and fertilizer pollution from irrigation return flows. A substantial amount of abatement, 50 percent or more, can be achieved at relatively low cost. However, it becomes very costly to reach abatement levels beyond those that can be achieved with managerial improvements, inexpensive shifts in irrigation systems, and sediment retention devices. There is reason to question the wisdom of investing in control practices which lead to complete or nearly complete abatement of pollution from irrigation return flows, for the last increments of abatement are achieved at extremely high cost. Only if demonstrated benefits can be found to justify such levels of abatement should they be undertaken.

In general, it has been shown that control practices focused on the abatement of sediment losses will have little effect on the abatement of nitrogen losses. That is because nitrogen and sediment losses result from two different phenomena, deep percolation and runoff, respectively. In order to simultaneously achieve the abatement of pollution from percolated and runoff waters, it is necessary to invest in more expensive irrigation systems and/or change to substantially less profitable cropping patterns. Again, choices must be made regarding the type and amount of pollution which is to be abated. Such choices should be based on the estimated costs of the achieved abatement and the perceived benefits to be derived. There is little reason to make expenditures for pollution abatement that substantially exceed derived benefits. The final choice of pollution control practice(s) must be governed by the problem(s) to be solved and the available funds for pollution abatement.

It should be noted that this study has only illustrated a methodology that can be followed in arriving at solutions for abating pollution from irrigation return flows. Each problem area must be analyzed for its own characteristics. Specific engineering, soils, and economic data must be collected and alternative control practices analyzed for efficiency and effectiveness in abating pollution. Choices must be made regarding the level of abatement to be achieved and the distribution of costs for such abatement.

While this analysis has not addressed the question of cost allocation for such activities, it is an important determinant of control practices to be selected. Public Law 95-217 amended PL 92-500 to state that up to 50 percent of abatement costs will be shared with farmers. There is no guarantee that this level

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of subsidy is the correct one, however. Moreover, it refers only to capital investment cost and does not reflect changes in farm income or desired levels of abatement to be achieved.

It generally will be easier to share costs incurred for capital investments in items such as new irrigation systems or ditch lining, though the level of subsidy that should be achieved is not clear. Public investment in capital items is generally assured of a long-term change in levels of pollution, whereas an expenditure for implementing an irrigation scheduling service or end-of-field filter strips has no assured effectiveness beyond the year of investment. If the objective of federal subsidies is to compensate the farmer for income losses, the year-to-year variations in farm income due to changes in crop prices or yields can raise uncertainties about the expenditure required to implement such short-run pollution controls.

The problems of sharing costs for temporary control practices versus costs of capital items with longer-lasting impacts raises an interesting conflict. In general, this analysis has shown that the most cost-effective measures of pollution abatement are those of a temporary or nonstructural nature. These temporary measures will be most difficult to administer, however. In the past, agencies such as the Soil Conservation Service have been reluctant to share costs of nonpermanent soil conservation practices. A similar attitude is expected to apply to practices for environmental protection. Thus, there remains a possibility that the most cost-effective control practices may be the most difficult to implement and administer.

Even after determining the optimal level of pollution abatement and selecting the best means of its achievement, there remains a difficult problem of determining the proper amount of costs to be shared with farmers. If we assume that farmers desire to maximize profits, it follows that any changes in farming practices or cropping patterns to reduce pollution will potentially decrease net farm income if no subsidies are involved. So what is the proper amount of subsidy to be paid to farmers in this scene? Should farmers be required to share the costs of pollution abatement, or should all costs be paid by other sectors of the economy, leaving the farmer no worse off than before? Certainly farmers will share in the benefits of pollution abatement through reduced soil erosion, cleaner water for irrigation, less ditch cleaning, etc. Also, if changes in farm income are the criteria for setting levels of cost sharing, there are serious problems in an a priori determination of program costs, since crop prices and yields must be projected in order to estimate farm income impacts.

These and other problems must be resolved before widespread pollution-abatement programs can be implemented in irrigated agriculture. This report provides a current estimate of techni-

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cal knowledge and abatement alternatives which can be applied to problems of water pollution involving irrigated agriculture. Both of these will change as experience is gained. The information herein is only a foundation on which to build.

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APPENDIX A

TABLE A-1. ESTIMATED SEASONAL RUNOFF AND DEEP PERCOLATION FOR MAJOR CROPS AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY

	Irrigation system						
Crop	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	Runoff (inches)[a]						
Alfalfa	16	13.3	7.7	0	6	2	0
Spring grain	11	9	5.1	0	4	1.3	0
Winter grain	12.5	10.4	5.8	0	4.5	1.5	0
Pasture	12.5	10.4	5.8	0	4.5	1.5	0
Peas	8.5	7	3.9	0	3	1	0
Field corn	17.2	14.3	9.3	0	7.7	1.2	0
Sugarbeets	22.4	18.5	12	0	9.9	1.6	0
Dry beans	18.9	15.3	9.5	0	7.9	1.2	0
Potatoes	28	22.4	13.8	0	11.3	1.7	0
	Deep Percolation (inches)						
Alfalfa	11.2	8.9	6.4	11.2	4.8	1	7.4
Spring grain	11	9	6.8	11	5.6	2.6	6.4
Winter grain	12.5	10.4	7.8	12.5	6.3	3	7.2
Pasture	12.5	10.4	7.8	12.5	6.3	3	7.2
Peas	9.4	7.8	5.9	9.4	4.8	2.5	7.2
Field corn	9.8	7.7	5.6	9.8	4.3	1.2	5.3
Sugarbeets	12.8	10	7.2	12.8	5.5	1.6	7
Dry beans	14.9	11.8	8.6	14.9	7	3	8.8
Potatoes	26	20.7	15.1	26	12.5	5.8	12.9

Note: Assumes silt loam and loam soils with 0.5 percent to 2 percent slopes.

[a] 1 inch = 2.54 cm.

EPA-287 (Cin.)
(4-76)

TABLE A-2. ESTIMATED SEASONAL DEEP PERCOLATION FOR MAJOR CROPS AND IRRIGATION SYSTEMS IN THE UMATILLA AREA[a]

Crop	Irrigation system	
	PCP	ICP
	- - - (inches/acre) - - -	
Alfalfa	5.1	2.4
Winter grain	3.1	1.5
Field corn	3.6	1.7
Dry beans	2.6	1.2
Early potatoes	3.5	1.7
Late potatoes	4.6	2.2

Note: Assumes sandy soils.

[a] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.

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(4-76)

TABLE A-3. ESTIMATED SEASONAL WATER APPLICATION REQUIREMENTS FOR MAJOR CROPS AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY

Crop	Irrigation system						
	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	(inches/acre)[a]						
Alfalfa	64	59	51	48	48	40	49
Spring grain	44	40	34	33	32	26	32
Winter grain	50	46	39	37.5	36	30	36
Pasture	50	46	39	37.5	36	30	36
Peas	34	31	26	25.5	24	20	26
Field corn	49	44	37	31.8	34	24	30
Sugarbeets	64	57	48	41.6	44	32	40
Dry beans	54	47	38	35.1	35	24	32
Late potatoes	80	69	55	52	50	33	43

Note: Assumes silt loam and loam soils with 0.5 percent to 5 percent slopes.

[a] 1 inch = 2.54 cm.; 1 acre = 0.405 hectare.

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(4-76)

TABLE A-4. ESTIMATED SEASONAL WATER APPLICATION REQUIREMENTS FOR MAJOR CROPS AND IRRIGATION SYSTEMS IN THE UMATILLA AREA

Crop	Irrigation system PCP	Irrigation system ICP
	- - -(inches/acre)[a] - - -	
Alfalfa	51	48
Winter grain	31	30
Field corn	36	34
Dry beans	26	24
Early potatoes	35	33
Late potatoes	46	44

Note: Assumes sandy soils.

[a] 1 inch = 2.54 cm.; 1 acre = 0.405 hectare.

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TABLE A-5. PHOSPHORUS FERTILIZER APPLICATION RATES FOR MAJOR CROPS IN THE MAGIC VALLEY AND UMATILLA AREAS

Crop	Phosphorus fertilizer Magic Valley[a]	Phosphorus fertilizer Umatilla Area[b]
	- - - - - (pounds/acre)[c] - - - - -	
Alfalfa	20	50
Wheat	22	30
Pasture	44	---
Peas	41	---
Field corn	44	160
Sugarbeets	64	---
Dry beans	13	70
Early potatoes	---	200
Late potatoes	67	200

[a] Source: Lindeborg (1970).

[b] Source: Holst (1978).

[c] 1 pound/acre = 1.12 kg/ha.

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TABLE A-6. NITROGEN APPLICATION RATES AND ESTIMATED NITRATE LEACHING LOSSES FOR MAJOR CROPS AND IRRIGATION SYSTEMS IN THE UMATILLA AREA

Crop	Nitrogen application rate		Nitrate leaching loss	
	PCP	ICP	PCP	ICP
	(pounds/acre)[a]			
Alfalfa hay	0	0	0	0
Winter grain	161	140	41.5	21.2
Field corn	202	173	57.6	29.0
Dry beans	151	135	34.0	17.7
Early potatoes	302	259	86.7	44.0
Late potatoes	403	329	142.8	68.0

Note: Assumes sandy soils.

[a] 1 pound/acre = 1.12 kg/ha.

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(4-76)

TABLE A-7. ESTIMATED SEDIMENT LOSS FOR MAJOR CROP TYPES AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY

	Irrigation system						
Crop type	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	- - - - - - - - - - - - - - (tons/acre)[a] - - - - - - - - - - - - - -						
Potatoes	18.0	15.4	9.2	0	7.4	0.35	0
Other row crops	7.2	6.2	3.7	0	2.9	0.14	0
Close-growing crops	0.46	0.37	0.16	0	0.11	0.02	0

Note: Assumes silt loam soils with 1.5 percent slopes.

[a] 1 ton = 0.908 metric tons; 1 acre = 0.405 hectare.

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(4-76)

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TABLE A-8. NITROGEN APPLICATION RATES AND ESTIMATED NITRATE LEACHING LOSSES FOR MAJOR CROPS AND ALTERNATIVE IRRIGATION SYSTEMS IN THE MAGIC VALLEY

Crop	Irrigation system						
	PFRW	IFRW	CTBK	PMPBK	GPIPE	MLTST	SDRL
	-Nitrogen Application Rate (pounds/acre)a/						
Alfalfa	0	0	0	0	0	0	0
Spring grain	101	99	96	101	95	93	99
Winter grain	101	99	96	101	95	92	98
Pasture	101	99	96	101	95	92	98
Peas	36	35	35	36	34	33	36
Field corn	202	193	190	202	186	178	192
Sugarbeets	176	171	169	176	165	157	170
Dry beans	31	30	29	31	29	28	31
Potatoes	221	212	203	221	198	185	209
	-Nitrate Leaching Loss (pounds/acre)-						
Alfalfa	0	0	0	0	0	0	0
Spring grain	12.2	10.4	7.6	12.2	7.1	4.1	10.2
Winter grain	13.4	11.4	9.1	13.4	7.7	4.4	11.0
Pasture	13.4	11.4	9.1	13.4	7.7	4.4	11.0
Peas	3.7	3.2	2.6	3.7	2.2	1.4	3.8
Field corn	28.1	18.7	16.2	28.1	12.6	4.8	18.0
Sugarbeets	24.2	20.0	17.1	24.2	13.3	5.0	19.2
Dry beans	4.2	3.5	2.8	4.2	2.4	1.3	3.8
Potatoes	50.8	41.6	31.6	50.8	26.9	13.6	36.8

Note: Assumes silt loam soils with 0.5 percent to 2 percent slopes.

a/ 1 pound/acre = 0.12 kg/hectare.

EPA-287 (Cin.)
(4-76)

TABLE A-9. ESTIMATED PER ACRE CROP PRODUCTION COSTS FOR THE STUDY AREAS[a]

Crop	Magic Valley irrigation system					Umatilla Area
	PFRW, IFRW, CTBK	PMPBK	GPIPE	MLTST	SDRL	PCP, ICP
Alfalfa	139.01	142.80	162.81	12.07	167.97	276.34
Wheat	89.46	93.25	113.26	157.45	118.42	119.82
Pasture	33.54	37.33	57.34	101.53	62.50	---
Peas	146.43	150.22	170.23	214.42	175.39	---
Field corn	164.44	168.23	188.24	232.43	193.40	200.37
Sugarbeets	245.18	248.97	268.98	313.17	274.14	---
Dry beans	163.87	167.66	187.67	231.86	192.83	177.67
Early potatoes	---	---	---	---	---	509.26
Late potatoes	389.77	393.56	413.57	457.76	418.73	563.62

Note: Exclude costs for: (1) land, management, and overhead; (2) land taken out of production for sediment and irrigation ponds of the pump-back and multi-set systems, respectively; and (3) costs for inputs and control practices included in Table A-10.

[a] 1 acre = 0.405 hectare.

EPA-287 (Cin.)
(4-76)

TABLE A-10. ADDITIONAL CROP PRODUCTION COSTS FOR THE STUDY AREAS

Item	Unit	Magic Valley	Umatilla Area
	- - - - - -	($/unit)	- - - - - -
Irrigation scheduling service:[a]			
Late potatoes	acre[b]	6.00	6.00
Other crops	acre	3.00	3.00
Inputs:			
Irrigation labor	hour	3.50	4.00
Energy[c]	KWH	0.0115	0.009
Nitrogen fertilizer	pound	0.17	0.20
Phosphorus fertilizer	pound	0.39	0.34
Sediment retention devices:			
Sediment pond	ton	3.17	---
Filter strips:			
Close-growing crops	acre	0.42	---
Row crops	acre	4.73	---

[a] Personal communication with Computerized Management Services, Twin Fall, Idaho, 1978.

[b] 1 acre = 0.405 hectare; 1 pound = 0.454 kg.; 1 ton = 0.908 metric ton.

[c] Source: Whittlesey, et al. (1978).

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EPA-287 (Cin.)
(4-76)

TABLE A-11. YIELDS AND PRICES FOR CROPS PRODUCED IN THE STUDY AREAS

Crop	Unit	Magic Valley		Umatilla Area	
		yield[a]	price	yield[b]	price[c]
Alfalfa hay	ton[d]	6	42.74[e]	7	64.38
Spring wheat	bu	85	2.71[e]	---	---
Winter wheat	bu	100	2.71[e]	90	3.16
Pasture	ton equiv.	5	31.00[f]	---	---
Peas	cwt	30	11.40[g]	---	---
Field corn, silage	ton	22	14.00[g]	165	2.57
Sugarbeets	ton	23	24.83[e]	---	---
Dry beans	cwt	22	16.07[e]	18	17.79
Early potatoes	cwt	---	---	320	3.70
Late potatoes	cwt	300	3.15[e]	460	2.85

[a] Source: Lindeborg (1970).

[b] Source: Nelson and Holst (1976).

[c] Source: Oregon State University County Statistics Program.

[d] 1 ton = 0.908 metric ton; 1 bushel = 35.2 liters; 1 hundredweight = 45.4 kg.

[e] Source: U.S. Department of Agriculture (1975, 1976, 1977).

[f] Source: Pfeiffer (1976); U.S. Department of Agriculture (1975, 1976, 1977).

[g] Source: Idaho Crop and Livestock Reporting Service (1977).

EPA-287 (Cin.)
(4-76)

TABLE A-12. ESTIMATED ENERGY REQUIREMENTS FOR PUMPING IRRIGATION WATER IN THE STUDY AREAS

Item	Magic Valley	Umatilla Area
	- - (KWH/acre-inch)[a] - -	
Delivery to farm	0	52[b]
Irrigation systems:		
Pump-back furrow (PMPBK)	9.33	---
Multi-set furrow (MLTST)	0.11	---
Side-roll sprinkler (SDRL)	30.01[c]	---
Center-pivot sprinkler (PCP, ICP)	---	37.84[c]

[a] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.

[b] Assumes a 500 foot lift and 125 KWH per acre-foot per 100 feet of lift.

[c] Source: Busch (1978).

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EPA-287 (Cin.)
(4-76)

TABLE A-13. ESTIMATED PER ACRE IRRIGATION LABOR REQUIREMENTS FOR THE STUDY AREAS

	Magic Valley					Umatilla Area
	irrigation system					
Crop	PFRW, IFRW	CTBK	PMPBK	GPIPE, MLTST	SDRL	PCP, ICP
	- - - - - - - Hours per Acre per Irrigation - - - - - - - - -					
	0.5[a]	1.0[a]	0.5[a]	0.02[b]	0.2[a]	0.031[c]
	- - - - - - - - Hours per Acre per Season[d] - - - - - - - - - -					
Alfalfa	3.0	6.0	3.0	0.12	1.2	0.6
Wheat	2.5	5.0	2.5	0.1	1.0	0.5
Pasture	2.5	5.0	2.5	0.1	1.0	---
Peas	2.5	5.0	2.5	0.1	1.0	---
Field corn	2.0	4.0	2.0	0.08	0.8	0.5
Sugarbeets	2.5	5.0	2.5	0.1	1.0	---
Dry beans	3.0	6.0	3.0	0.12	1.2	0.6
Early potatoes	---	---	---	---	---	1.2
Late potatoes	6.5	13.0	6.5	0.26	2.6	1.6

Note: The assumed soil textures are silt loams or loams for the Magic Valley, and sands for the Umatilla Area.

[a] Source: Gossett (1975).

[b] Source: Worstell (1978).

[c] Source: Busch (1978).

[d] 1 acre = 0.405 hectare.

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EPA-287 (Cin.)
(4-76)

TABLE A-14. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE PRESENT FURROW IRRIGATION SYSTEM (PFRW), IMPROVED FURROW IRRIGATION SYSTEM (IFRW), AND THE CUT-BACK FURROW IRRIGATION SYSTEM (CTBK) ON THE MAGIC VALLEY MODEL FARM

	Cost	
Item	$/acre[a]	$/300 acres
Capital investment:[b]		
Aluminum tubes[c]	6.42	
Field equipment:		
"V" ditcher[d]	2.40	
Corrugator, headland[e]	5.00	
Total capital investment	13.82	4,146
Annual costs:		
Ownership costs:		
Depreciation (15 yrs, 10% salvage)	.83	
Interest on average investment (9%)	.62	
Total ownership costs	1.45	435
Operating costs:[f]		
Maintenance, field equipment[g]	.22	
Corrugation, ditch, and headland maintenance[h]	6.50	
Interest on operating capital (6 mo. @ 9%)	.30	
Total operating costs	7.02	2,121
Total annual costs	8.47	2,556

Note: The capital investment and annual costs for each irrigation system used on the farm (300 acres) are based upon average per acre estimates which, in turn, are based on an assumed system size. This is the case for the irrigation systems in this table, as well as the remaining irrigation systems in the following tables. A change in the assumed system size may change the per acre capital investment and annual costs and, as a result, may change these values for the total farm.

[a] 1 acre = 0.405 hectare; 1 foot = 30.48 cm.

[b] Assumes: aluminum tubes--head ditches of 880 feet per 20 acres, 1 tube per 4 rows, 0.106 tubes per foot; "V" ditcher--$720; corrugator--$1,500 for the 300-acre farm.

[c] Source: Irrigation equipment dealers in Washington, personal communications, 1978.

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(4-76)

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d/Source: Doran and Foeppel (1974).

e/Source: Willett, et al. (1978).

f/Excludes irrigation labor and irrigation scheduling service costs.

g/Assumed to be 3 percent of total capital investment.

h/Source: Fitzsimmons, et al. (1978); Doran and Foeppel (1974).

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TABLE A-15. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE PUMP-BACK FURROW IRRIGATION SYSTEM (PMPBK) ON THE MAGIC VALLEY MODEL FARM

Item	Cost $/acre[a]	 $/300 acres
Capital investment:		
Present investment[b]	13.82	4,146
Additional investment:[c]		
Pump	1.88	
Pipe	31.69	
Total additional investment	36.07	10,821
Total capital investment	49.84	14,967
Annual costs:		
Ownership costs:		
Depreciation:		
Present investment (15 yrs, 10% salvage)	.83	
Additional investment:		
Pump (20 yrs, 10% salvage)	.20	
Pipe (20 yrs, 0 salvage)	1.58	
Interest on average investment (9%)	2.25	
Total ownership costs	4.86	1,458
Operating costs:[d]		
Maintenance on present investment[e]	.58	
Corrugation, ditch, and headland maintenance	6.50	
Interest on operating capital (6 mo. @ 9%)	.32	
Total operating costs	7.40	2,220
Total annual costs	12.26	3,678

---

[a] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.; 1 foot = 30.48 cm.

[b] Aluminum tubes and field equipment of the present furrow system.

[c] Source: L.G. King, personal communication, Department of Agricultural Engineering, Washington State University, 1978. Assumes: (1) system design for 160 acres; (2) pump--10 h.p., $300; (3) pumping energy requirement--9.33 KWH/acre-inch; (4) pipe (PVC)--6 inches, 2,640 feet @ $1.92.

[d] Excludes irrigation labor, pumping energy, and sediment and related costs.

[e] Assumed to be the sum of the maintenance of the present investment and 1 percent of the additional investment.

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TABLE A-16. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE GATED-PIPE FURROW IRRIGATION SYSTEM (GPIPE) ON THE MAGIC VALLEY MODEL FARM

	Cost	
Item	$/acre[a]	$/300 acres
Capital investment:		
Present investment[b]	7.40	2,220
Additional investment[c]	179.48	53,844
Total capital investment	186.88	56,064
Annual costs:		
Ownership costs:		
Depreciation, total investment (15 yrs, 10% salvage)	11.21	
Interest on average investment (9%)	8.41	
Total ownership costs	19.62	5,886
Operating costs:[d]		
Maintenance[e]	5.61	
Corrugation, ditch, and headland maintenance	6.50	
Interest on operating capital (6 mo. @ 9%)	.54	
Total operating costs	12.65	3,795
Total annual costs	32.27	9,681

---

[a] 1 acre = 0.405 hectare; 1 foot = 30.48 cm.; 1 inch = 2.54 cm.

[b] Field equipment of the present furrow system; aluminum tubes are not included.

[c] Source: Worstell (1978). Assumes: (1) system design for 40 acres; (2) aluminum gated-pipe--1,300 feet of 8 inch, $2.28 per foot; (3) miscellaneous--tees, risers, air valves, end plugs, airline, $0.89 per foot; (4) timer--controller, air compressor, and miscellaneous--$40 per acre.

[d] Excludes irrigation labor and scheduling service costs.

[e] Assumed to be 3 percent of the total investment.

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(4-76)

TABLE A-17. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE MULTI-SET FURROW IRRIGATION SYSTEM (MLTST) ON THE MAGIC VALLEY MODEL FARM

Item	Cost	
	$/acre[a]	$/300 acres
Capital investment:		
Present investment[b]	7.40	2,220
Additional investment:		
Multi-set system[c]	550.00	
Pump[d]	12.50	
Pond[e]	6.80	
Total additional investment	569.30	170,790
Total capital investment	576.70	173,010
Annual costs:		
Ownership costs:		
Depreciation:		
Present investment (15 yrs, 10% salvage)	.44	
Multi-set system, pump (20 yrs, 10% salvage)	24.75	
Pond (15 yrs, 0 salvage)	.45	
Interest on average investment (9%)	25.95	
Total ownership costs	51.59	15,477
Operating costs:[f]		
Maintenance[g]	17.30	
Corrugation, ditch, and headland maintenance	6.50	
Interest on operating capital (6 mo. @ 9%)	1.07	
Total operating costs	24.87	7,461
Total annual costs	76.46	22,938

[a] 1 acre = 0.405 hectare; 1 inch = 2.54 cm.; 1 cubic yard = 0.765 cubic meters.

[b] Field equipment of the present furrow system; aluminum tubes are not included.

[c] Source: Worstell (1976). Assumes a system design of 40 acres.

[d] Source: L.G. King, personal communication, Department of Agricultural Engineering, Washington State University, 1978. Assumes: (1) size--3 h.p.; (2) cost--$500; (3) energy requirement--0.11 KWH/acre-inch.

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PAGE NUMBER

EPA-287 (Cin.)
(4-76)

TABLE A-17. CONTINUED

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[e] Source: Conklin, et al. (1978). Assumes 200 cubic yards @ $1.36. The opportunity cost of taking cropland out of production is not included.

[f] Excludes irrigation labor, pumping energy, and the irrigation scheduling service costs.

[g] Assumed to be 3 percent of the total capital investment.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE A-18. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE SIDE-ROLL SPRINKLER IRRIGATION SYSTEM (SDRL) ON THE MAGIC VALLEY MODEL FARM

	Cost	
Item	$/acre[a]	$/300 acres
Capital investment:		
Side-roll sprinkler system:[b]		
Mainline	49.46	
Laterals	203.46	
Pump	28.21	
Pond[b]	6.80	
Ditch fill[c]	7.52	
Total capital investment	295.45	88,635
Annual costs:		
Ownership costs:		
Depreciation:		
Laterals (15 yrs, 10% salvage)	12.21	
Mainline, pump (20 yrs, 10% salvage)	3.50	
Pond, ditch fill (15 yrs, 0 salvage)	.95	
Interest on average investment (9%)	13.30	
Total ownership costs	29.96	8,988
Operating costs:[d]		
Maintenance[e]	7.15	
Interest on operating capital (6 mo. @ 9%)	.32	
Total operating costs	7.47	2,241
Total annual costs	37.43	11,229

[a] 1 acre = 0.405 hectare; 1 cubic yard = 0.765 cubic meters.

[b] Source: Conklin, et al. (1978). Assumes: (1) system design for 140 acres; (2) pump size--50 h.p.; (3) pond--700 cubic yards @ $1.36.

[c] Assumes: (1) 293 yards each of head and tail ditches for a 20-acre field or 2,053 yards each for 140 acres; (2) head ditch fill--516 cubic yards @ $1.36; (3) tail ditch fill--258 cubic yards @ $1.36. Cropland gained by filling in ditches is assumed to offset that required by the pond.

[d] Excludes irrigation labor, pumping energy, and the irrigation scheduling service costs.

[e] Assumed to be 3 percent of the capital investment in the laterals, pump, and pond.

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EPA-287 (Cin.)
(4-76)

TABLE A-19. ANNUAL COSTS FOR FILTER STRIPS ON THE MAGIC VALLEY MODEL FARM

Item	Cost close-growing crops	 row crops
	- - - ($/acre)[a]	- - -
Seeding[b]	0.13	0.20
Sediment spreading[c]	0.29	4.53
TOTAL COST	0.42	4.73

Source: Conklin, et al. (1978).

Note: The opportunity cost for land taken out of production is not included. Capital investment is not required.

[a] 1 acre = 0.405 hectare; 1 foot = 30.48 cm.; 1 cubic yard = 0.765 cubic meters; 1 ton = 0.908 metric ton.

[b] Assumes: filter strip--8 x 880 feet, or 0.162 acres per 20 acre field. This would be 0.0081 acres per acre of cropland.

[c] Assumes: (1) the sediment loss estimates for spring wheat and dry beans of Table A-7 and 50 percent retention of sediment loss; (2) spring wheat--80 acres; dry beans--60 acres; (3) a sediment density of 0.926 cubic yards per ton, and a cost of $0.68 per ton.

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TABLE A-20. ESTIMATED ANNUAL CROP PRODUCTION COSTS IN THE MAGIC VALLEY

Item	Crop							
	alfalfa[a]	wheat[a]	pasture[b]	peas[a]	field corn [a]	sugar-beets [a]	dry beans[a]	potatoes[a]
	($/acre)[c]							
Operating costs:								
Seed	---	8.50	---	37.13	18.81	4.00	24.00	115.00
Fertilizer[d]	3.50	3.50	3.50	3.50	16.90	3.50	7.25	35.50
Herbicide	---	5.00	---	6.50	10.00	8.00	18.00	18.08
Insecticide	3.00	---	---	8.00	---	8.40	8.00	20.78
Water	4.88	4.88	4.88	4.88	4.88	4.88	4.88	4.88
Custom[e]	20.00	22.50	---	---	13.50	---	---	---
Fuel, labor, repairs (tractors, equipment)	10.42	5.68	---	11.70	15.40	39.40	16.75	33.05
Labor:								
Machine ($3.75/hr)	8.30	11.10	---	15.23	20.25	42.96	23.68	33.19
Other ($3.50/hr)	---	---	---	---	---	46.90	---	7.00
Miscellaneous[f]	---	---	---	---	---	8.40	---	22.60
Interest on operating capital (6 mo. @ 9%)	2.25	2.75	0.38	3.91	4.49	7.11	4.62	12.70
Total operating costs	52.35	63.91	8.76	90.85	104.23	165.10	107.18	295.24
Ownership costs:[g]								
Tractors, equipment	31.79	17.08	---	47.11	51.74	71.62	48.23	86.06
Stand investment	45.40	---	16.31	---	---	---	---	---
Total ownership costs	77.19	17.08	16.31	47.11	51.74	71.62	48.23	86.06
TOTAL COST	130.54	80.99	25.07	137.96	155.97	236.72	155.41	381.30

Note: Costs were updated to early 1978; excludes all costs related to irrigation.

[a] Source: Lindeborg (1976).

[b] Source: Pfeiffer (1976).

[c] 1 acre = 0.405 hectare.

[d] Excludes nitrogen and phosphorus fertilizer; includes a fertilizer application cost of $3.50 ($16.50 for potatoes).

[e] Includes: (1) alfalfa--custom stack; (2) wheat--custom combine; (3) field corn--custom plow.

[f] Includes: (1) sugarbeets--sulfur dust (fungicide); (2) potatoes--blight control (fungicide).

[g] Includes depreciation, interest on average investment at 9 percent, taxes, and insurance. Assumes a stand life of 3 years for alfalfa and 10 years for pasture.

EPA-287 (Cin.)
(4-76)

TABLE A-21. CAPITAL INVESTMENT AND ANNUAL COSTS FOR THE PRESENT CENTER-PIVOT SPRINKLER (PCP) AND THE IMPROVED CENTER-PIVOT SPRINKLER (ICP) SYSTEMS ON THE UMATILLA AREA MODEL FARM

Item	Cost	
	$/acre[a]	$/1,300 acres
Capital investment:[b]		
Mainline	92.00	
Lateral	218.00	
Pumps and miscellaneous	63.65	
Total capital investment	373.65	485,745
Annual costs:		
Ownership costs:		
Depreciation:		
Lateral (15 yrs, 10% salvage)	13.87	
Mainline, pumps, miscellaneous (20 yrs, 10% salvage)	7.00	
Interest on average investment (9%)	16.81	
Total ownership costs	37.68	48,990
Operating costs:[c]		
Maintenance[d]	8.45	
Interest on operating capital (6 mo. @ 9%)	.38	
Total operating costs	8.83	11,473
Total annual costs	46.51	60,463

Source: Holst (1978).

Note: Costs were current from spring, 1978.

[a] 1 acre = 0.405 hectare; 1 foot = 30.48 cm.

[b] Assumes: (1) a system design for 130 acres; (2) lateral--1,320 feet.

[c] Excludes irrigation labor, pumping energy, and the irrigation scheduling service costs.

[d] Assumed to be 3 percent of the capital investment in laterals, pump, and miscellaneous.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE A-22. ESTIMATED ANNUAL CROP PRODUCTION COSTS IN THE UMATILLA AREA

Item	Crop					
	alfalfa	wheat	field corn	dry beans	early potatoes	late potatoes
	($/acre)[a]					
Operating cost:						
Seed	---	8.10	18.81	33.30	149.50	130.00
Fertilizer[b]	10.81	5.55	23.35	10.35	35.24	35.24
Herbicide[c]	18.50	5.50	17.18	6.38	9.10	10.25
Insecticide[d]	---	---	6.75	---	57.20	86.00
Custom haul	---	7.20	13.20	5.40	64.00	92.00
Fuel, lube, repairs (tractors, equipment)	31.48	13.11	19.36	19.46	42.39	42.39
Labor (machine operations)	29.53	8.37	13.95	14.32	23.84	23.84
Miscellaneous[e]	11.40	---	---	---	---	13.57
Interest on operating capital (6 mo. @ 9%)	4.00	2.15	5.07	4.01	17.16	19.50
Total operating cost	106.30	49.98	117.67	93.22	398.43	452.79
Ownership cost:[f]						
Tractors, equipment	85.84	23.33	36.19	37.45	64.32	64.32
Alfalfa stand	37.69	---	---	---	---	---
Total ownership cost	123.53	23.33	36.19	37.45	64.32	64.32
TOTAL COST	229.83	73.31	153.86	130.67	462.25	517.11

Source: Holst (1978).

Note: Costs were current for spring, 1978; excluding all costs related to irrigation.

[a] 1 acre = 0.405 hectare.

(continued)

TABLE A-22. CONTINUED

[b] Excludes nitrogen and phosphorus fertilizer; includes spreader rent of $10.75.

[c] Includes an application cost of $3.00 and defoliant for early potatoes of $6.10 plus $3.00 for application.

[d] Includes an application cost of $3.00 ($6.00 for potatoes).

[e] Includes: (1) alfalfa--gopher control bale wire; (2) late potatoes--pesticide and application.

[f] Includes depreciation, interest on average investment at 9 percent, taxes, and insurance. Assumes a 5-year stand life for alfalfa.

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EPA-287 (Cin.)
(4-76)